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PETROLOGY OF SOME LOWER CRETACEOUS SANDSTONES OF THE NORTHERN
RICHARDSON MOUNTAINS NEAR STONY CREEK, NORTHWEST TERRITORIES

by



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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Petrology of Some Lower Cretaceous Sandstones of the Northern Richardson Mountains near Stony Creek, Northwest Territories" submitted by Robert Lars Nowak in partial fulfillment of the requirements for the degree of Master of Science.

June, 1971



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ABSTRACT

A diagenetic oriented lithologic and petrographic study was conducted on sandstone cores of the Upper Sandstone Division of mid-Lower Cretaceous age from three stratigraphic wells along Stony Creek, Northwest Territories. These Upper Sandstone Division sediments were deposited in a fluctuating transgressive-regressive system marked by rapid subsidence and transgression followed by slower regression, which resulted in the development of a series of fluctuating sandstone shoals.

Examination of the mineralogy of these sediments revealed the following authigenic minerals: silica, chlorite, calcite, siderite, glauconite, chamosite, kaolinite, pyrite, feldspar, hydromuscovite, and hydrous oxides. Paragenetic relationships show the glauconite and chamosite pellets to be penecontemporaneous in origin and therefore the first authigenic minerals to form. This is followed by the formation of chlorite cement and authigenic silica overgrowths, sometimes in reverse order. Precipitation of the carbonates (calcite and siderite) occurred next, followed by the late stage development of feldspar, hydromuscovite, and pyrite.

The distribution of authigenic minerals (based on the Eh and pH of the interstitial fluids) in their stratigraphic sequence reveals six diagenetic zones and four diagenetic facies reflecting depositional conditions existing at the time of mid-Lower Cretaceous sedimentation.

It is possible to predict diagenetically controlled porosity which is related to the presence of clay rock fragments and quartz framework grains. The squeezed and unsqueezed clay rock fragments inhibit the

precipitation of chemical cements, thereby preserving porosity. A number of generalities are inferred: 1) chert-rich sandstones serve as potential petroleum reservoirs at shallow depths; 2) the best reservoir is a matrix-free quartzose sandstone with either clay coatings or thin chlorite rims on the quartz grains, or a quartzose sandstone containing unsqueezed or partially squeezed clay pellets; 3) the landward side of the shoal generally contains the higher porosity, although where the chert content is substantial, either landward or seaward side may show good porosity.

INTRODUCTION

Area of study

The study area is located on the eastern slope of the North Richardson Mountains in the District of Mackenzie, Northwest Territories (Fig. 1). The Richardson Mountains form a straight and relatively narrow belt of comparatively rough country between the Peel Plateau on the east and the Porcupine Plain and Arctic Plateau on the west and form a continuous water-shed throughout their length. For the most part the Richardson Mountains are lower than the southern foothills of the Canadian Rocky Mountains, which they resemble somewhat in their bare slopes (Bostock, 1948).

Beds on the eastern flank of the Richardson Mountains have dips of 25 to 40 degrees in a westerly direction, with many of the ridges having an asymmetrical cross-section. All the rocks involved are sedimentary, consisting of thick sections of sandstones and shale. If any part of the Richardson Mountains has suffered Pleistocene glaciation, the effects were slight, as the ice did not produce any noticeable moraines on the east flank, except in parts of the Peel Plateau.

Previous work

The Geological Survey of Canada has been conducting mapping parties in the Richardson Mountain area for twelve years and is the only source of published work in this area. The first geological reconnaissance was carried out in 1956 by Gabrielse, but the most extensive work in the area has been done by Jeletzky, the "father" of Mesozoic stratigraphy in the Yukon and Northwest Territories, who published papers in 1958,

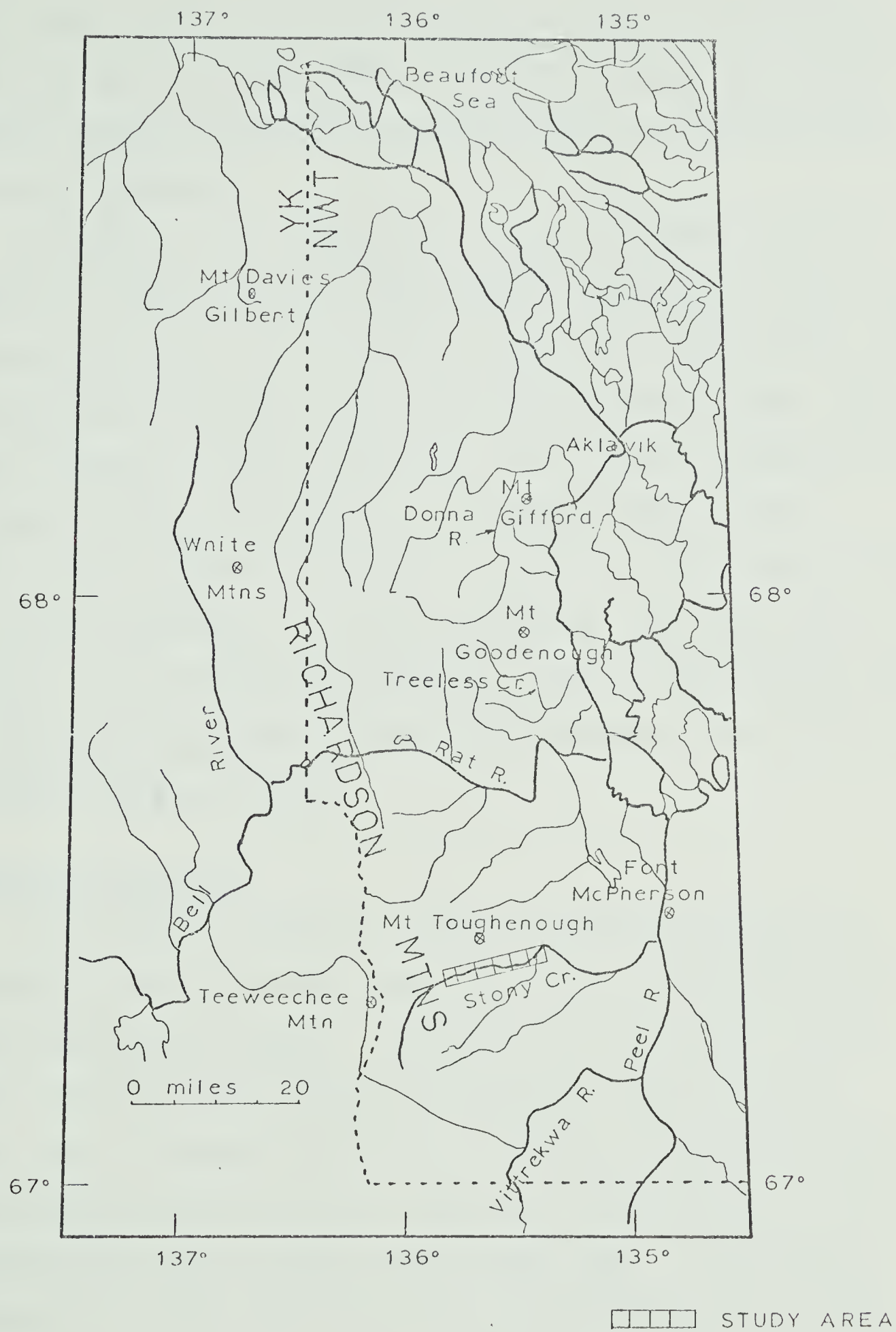


Figure 1: Index map

1960, 1961, and 1966. Other contributions to Mesozoic stratigraphy have been made by Mountjoy (1966a, 1966b) and two papers dealing with Canadian Mesozoic fossils were published in 1964, one by Jeletzky and the other by McGregor.

In addition to the work carried out by the Geological Survey of Canada, the north has become a prime target of exploration by major oil companies during the last five years in particular. Unfortunately, the oil companies are reluctant to do much publishing on the north. Most of their information is still confidential and is likely to remain so for a number of years. In addition to the Mackenzie Delta, several wells have been drilled in the Eagle Plains area in the southern portion of the Yukon Territory. At the time of writing, three wells have been drilled in the Richardson Mountain area. These are stratigraphic wells C2, F42, and F52A drilled by Imperial Oil Enterprises, with information released in August of 1969.

Purposes of the study

To the writer's knowledge no detailed petrologic work has been attempted to date on Mesozoic rocks of the Yukon and Northwest Territories beyond stratigraphic mapping. Permission from Imperial Oil to study the Lower Cretaceous rocks of Stony Creek from their F52A, F42, and C2 wells (Fig. 2) prompted the writer to undertake a petrographic study. The wells are ideally suited to a diagenetic oriented study, as they are stratigraphic wells and hence are completely cored. In addition, in attempting to define diagenetic facies it is helpful to have a study area whose geological history is limited to normal sedimentary processes

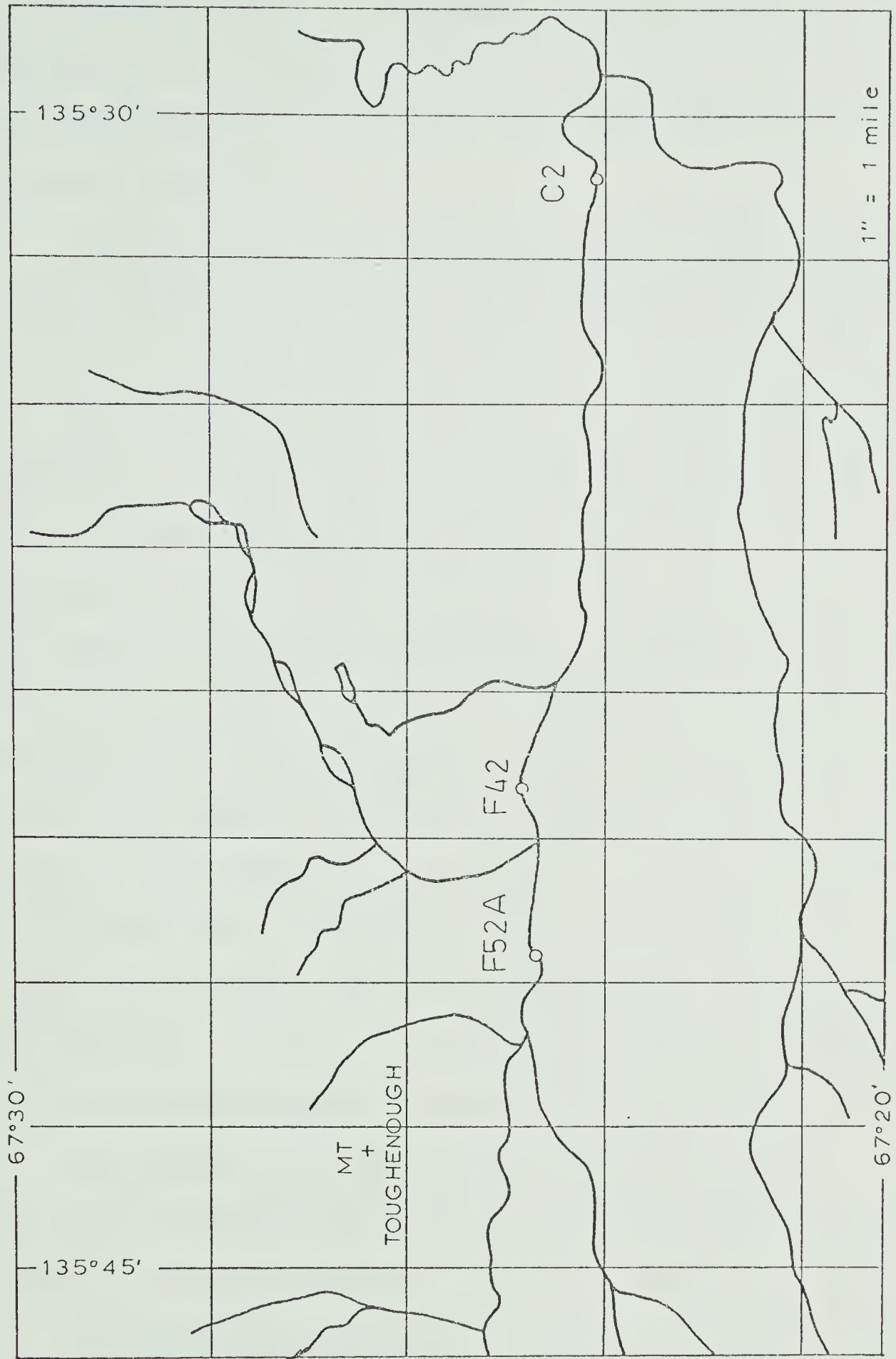


Figure 2: Well location map

*courtesy Imperial Oil

with tectonic activity at a minimum. It was also preferable to do a subsurface study in order to eliminate the effects of recent weathering. For these reasons the Stony Creek wells were chosen for a study of sandstone diagenesis.

The prime purpose of the research was to discover any systematic trends in diagenetic "facies". It was hoped that any such trends would be useful in predicting areas where processes of sandstone diagenesis had been most conducive to producing sandstones with optimum reservoir properties. In addition, it was expected that early authigenic minerals would shed some light on the chemical conditions and hence on the paleogeographic settings of the depositional sites. The basic approach to the problem of diagenesis is descriptive; authigenic minerals have been identified and described, and their paragenetic relationships established when possible. It was hoped that a study of the secondary minerals would reveal patterns which could be explained in terms of processes operating after deposition of the sands. A number of important papers, particularly those of Waldschmidt (1941), Heald (1950, 1956), Gilbert (1949) and Fothergill (1955) have been published dealing with cementation of sandstones. However, to the writer's knowledge no attempt has been made to establish diagenetic "facies" and to map these facies.

The purposes of the study may be itemized as follows:

1. To make a detailed study of the quantitative distribution of authigenic or secondary minerals, noting their paragenetic relationships.
2. To define diagenetic facies in terms of the secondary minerals observed.

3. To search for reasons for variations in kind and degree of cementation.
4. To try to correlate the diagenetic facies.

Methods and materials

The primary approach to this study was petrographic with restriction to the Upper Sandstone Division of late Upper Barremian to Lower Aptian age as defined by Jeletzky, 1958. The rocks were studied in thin section and several parameters chosen for quantitative evaluation. A total of 102 thin sections were studied, 42 of which were point-counted in detail. To avoid bias the slides were studied in random order. After staining for potash feldspar, three separate 100 grain point-counts were made on each of the 42 slides to determine quantitatively the essential, varietal, and accessory minerals. In addition, a 50 grain count was done on each slide to determine the "packing proximity". The remaining 60 thin sections served to supply additional information on the authigenic minerals and their paragenetic relationships.

A number of X-ray diffraction patterns were run on shale samples above and below the sandstone units of prime interest to examine any difference in clay mineralogy, and analytical checks were carried out on the microprobe to corroborate petrographic identification of glauconite, chamosite, and siderite.

GEOLOGIC SETTING

Stratigraphy

The predominantly marine uppermost Jurassic and Lower Cretaceous sequence of the eastern slope of the northern Richardson Mountains has been fairly well defined by Jeletzky (1958, 1960, 1961) who has subdivided this lithologic sequence into five divisions with the succession based on fossil zones. These divisions are: a Lower Shale-Siltstone of uppermost Jurassic and lowermost Cretaceous age, a Lower Sandstone of early Lower Cretaceous age, an Upper Shale-Siltstone of mid-Lower Cretaceous age, and an Upper Sandstone also of mid-Lower Cretaceous age (Table 1).

Lower Shale-Siltstone Division:

The Lower Shale-Siltstone Division consists of a monotonous succession (1670+ feet; Jeletzky, 1961) of shales and siltstones with minor localized pockets of shell debris. The division is subdivisible into a lower and an upper member. The lower member consists predominantly of shale, silty shale, and siltstone interbedded with minor beds of sandy siltstones, fine grained shaly sandstones, and thin beds of conglomeratic sandstone. Throughout this member may be found horizons of concretions and layers of clay ironstone. The upper member is characterized by sandy siltstones and shale interbedded with laminae of silty, shaly sandstone which increase upward both in thickness and in number. Toward the top of the upper member these dark grey fine grained sandstones become light grey to buff in color and resemble sandstones characteristic of the overlying Lower Sandstone Division. Concretions and clay ironstone layers are also common throughout the

TABLE 1

Table of formations	
Stage	Lithological Division
Late-Lower Cretaceous (late Upper Aptian-Albian)	Albian Shale-Siltstone Division
Mid-Lower Cretaceous (late Upper Barremian-Aptian)	Upper Sandstone Division b) grey sandy siltstone member a) conglomeratic member
(late Upper Hauterivian-Upper Barremian)	Upper Shale-Siltstone Division b) upper member a) lower member
Early-Lower Cretaceous to mid-Lower Cretaceous (early Valanginian to late Upper Hauterivian)	Overlap and erosional gap
Early-Lower Cretaceous (late Berriasian-early Valanginian)	Lower Sandstone Division b) white sandstone member a) buff sandstone member
Upper Jurassic to early-Lower Cretaceous (Lower Callovian-early Berriasian)	Lower Shale-Siltstone Division b) upper member a) lower member

upper member. The contact between the lower and upper members is gradational. Westward and southward the predominantly shale facies of the Lower Shale-Siltstone Division gives way to arenaceous equivalents. This change to shallower water deposits takes place near the headwaters of Stony Creek, where the rocks become glauconitic sandstones and conglomerates. The Lower Shale-Siltstone Division has been measured in sections from Mount Gifford to Vittrekwa River (Fig. 1) (Jeletzky, 1958).

Lower Sandstone Division:

The Lower Sandstone Division is characterized by a succession (600-650 feet; Jeletzky, 1958) of sandstones with minor intercalated beds of siltstone and shale. The division can be subdivided lithologically into a buff sandstone member and an overlying white sandstone member. In the north (Donna River, Fig. 1), the white sandstone is overlain gradationally by the Coal-bearing Division which disappears southward on the erosional unconformity (Jeletzky, 1958) between the older Lower Cretaceous and mid-Lower Cretaceous rocks and hence is not found in the Stony Creek area. In the Donna River area where the coal bearing unit is present it consists of two members; a lower member of carbonaceous to coaly sandstones reflecting regression of the early Lower Cretaceous sea and an upper member of quartzose, fine to medium grained sandstones with abundant cross-bedding and ripple marks. The upper member contains small nests of carbonaceous to coaly sandstone.

The buff sandstone member (350-370 feet; Jeletzky, 1958) is composed of fine grained, thinly bedded quartzose and micaceous sandstone which varies from hard to friable and is interbedded with layers of friable,

clayey to silty, fine grained sandstone. The overlying white sandstone member consists of a thick succession (150-350 feet; Jeletzky, 1958) of fine to coarse grained quartzose sandstones, many of which in the lower half are strongly cross-bedded and concretionary. The upper half of the white sandstone member is commonly carbonaceous with thin layers of grit and pebble conglomerate. The contact between the buff sandstone member and the white sandstone member is gradational.

The white sandstone member has not yielded any marine fossils. This lack, plus the presence of carbonaceous matter, suggests a largely continental origin in contrast to the underlying buff sandstone member which is marine in origin on the basis of its fossil content. The Lower Sandstone Division rocks typically occur in the Mount Toughenough and headwaters of Stony Creek area. From Treeless Creek southwestward to Teeweechee Mountain (Fig. 1) the Lower Sandstone Division rocks are absent due to erosion prior to deposition of the Upper Shale-Siltstone Division.

Upper Shale-Siltstone Division:

Rocks of the Lower Sandstone Division are unconformably overlapped by a succession (1100-1200 feet; Jeletzky, 1958) of marine shales, siltstones, and sandstones. The lithology and thickness of this division closely matches that of the Lower Shale-Siltstone Division, and the sequence is recognized as a repeated shale-siltstone cycle (Jeletzky, 1958). The Upper Shale-Siltstone Division is composed of marine shales and siltstones with abundant clay ironstone concretions and beds. It can be subdivided into two members; The lower member contains dark

shales with abundant horizons of clay ironstone concretions, while the upper member is composed of greyish-black sandy siltstones and silty fine grained sandstones in approximately equal amounts. Where exposed, a basal conglomerate of the Upper Shale-Siltstone Division lies disconformably on the older rocks.

The southward facies changes of the Upper Shale-Siltstone Division parallel those of the Lower Shale-Siltstone Division. Jeletzky (1960) states that the rocks of the two divisions are lithologically indistinguishable on Barrier Creek and near the headwaters of Stony Creek. The Upper Shale-Siltstone Division has been recognized in sections from Mount Gifford south to the Vittrekwa River and shows a major transgressive overlap of the older rocks southward.

Upper Sandstone Division:

The Upper Sandstone Division is composed of light grey or buff sandstone which is fine to medium grained, well sorted, quartzose, and micaceous. It occurs as 90-150 foot thick units interbedded with units of fine grained, soft shaly sandstone, sandy siltstone, shale, and clay ironstone of approximately the same thickness (Jeletzky, 1958, 1960). Conglomerates and conglomeratic sandstones and occasionally glauconitic sandstones occur as interbeds near the base of the division on Rat River and Stony Creek. Complete Upper Sandstone Division sections have not been observed from Donna River south to Rat River. In these locales no lower and upper members have been identified. However, at Stony Creek the Upper Sandstone Division is divisible into a lower conglomeratic

member and an upper grey sandy siltstone member. The conglomerates and conglomeratic sandstones at Stony Creek are much thicker here than those occurring as interbeds at Rat River. The grey sandy siltstone member is only about 40 feet thick at Stony Creek but thickens southward to 250 feet in the Vittrekwa River area (Jeletzky, 1960). Facies changes toward the south and southeast also occur in the lower part of the Upper Sandstone Division. These changes are believed to be related to the increasing proximity of the southern and southeastern shore of the mid-Lower Cretaceous sea (Jeletzky, 1960). Arenaceous rocks, particularly in the Vittrekwa and Stony Creek areas give way to shaly sandstones and sandy siltstones along the Donna River further north, to the extent that the lithological distinction between the lower part of the Upper Sandstone Division and the underlying Upper Shale-Siltstone Division disappears. An advance of the mid-Lower Cretaceous sea during Upper Aptian time is reflected by overlap of Paleozoic rocks by the grey sandy siltstone member in the Stony Creek area. Lithologies of the Upper Sandstone and Lower Sandstone Divisions are indistinguishable.

The Upper Sandstone Division is best observed from Donna River southward to the Vittrekwa River. It is thickest between Treeless Creek and Donna River (800-900 feet), thins substantially around Stony Creek (410 feet), and then increases slightly toward the Vittrekwa River (500-600 feet). The decrease in thickness in the Stony Creek area has been attributed to erosion (Jeletzky, 1960) but the magnitude of the eroded interval is uncertain. Contact between the Upper Sandstone Division and the overlying Albian Shale-Siltstone Division is exposed only in the

Stony Creek sections.

Because the pelecypod fauna consists of long ranging forms the Upper Sandstone Division is difficult to date. The lower part is either Lower Aptian or uppermost Barremian (Jeletzky, 1958). It is not certain whether or not the middle and upper part of the Upper Sandstone Division is of comparable age.

Albian Shale-Siltstone Division:

Overlying the Upper Sandstone Division, rocks of an Albian Shale-Siltstone Division are widespread along the Peel and Vittrekwa Rivers. In this area they occupy a depositional low which extends northward into the Stony Creek area (Jeletzky, 1960). These rocks are found at Stony Creek and Mount Toughenough but not in the more northerly areas, where they were lost by erosion before deposition of the overlying division.

The Albian Shale-Siltstone Division is characterized by hard shales and siltstones with numerous interbeds of clay ironstone and clay ironstone concretions. Much of the siltstone is fairly sandy with shaly sandstones occurring in the lower part of the succession. Contact with the underlying Upper Sandstone Division is everywhere sharp and uneven with a pebble conglomerate generally filling depressions.

Geologic history

The Richardson Mountain trough was a north trending basin present during much of the Jurassic (Martin, 1959) and at least part of the early Lower Cretaceous. The early Lower Cretaceous marine rocks were deposited from a southern extension of the Arctic transgression that flooded most of northern Alaska and part of the Queen Charlotte Archipelago. The

early Lower Cretaceous sea withdrew from the area around Middle Valanginian time. The regression of this sea is reflected in the rocks of the Lower Sandstone Division. The lithological change from shale-siltstone to sandstone indicates a shallowing of the early Lower Cretaceous sea. However, sedimentation must have continued without interruption, as the contact is gradational between the Lower Shale-Siltstone and Lower Sandstone Divisions. The shallow water nature of the Lower Sandstone Division indicates increasing proximity to the regressing shoreline. Further evidence of regression is reflected in the difference between the two members of the Lower Sandstone Division. The lower or buff sandstone member is marine, whereas the upper or white sandstone member is probably non-marine.

Uplift of the Richardson Mountains took place during Middle Valanginian to Middle Hauterivian but was largely restricted to the southern part of the area. Jeletzky (1960) states, "Farther north, between Bug Creek and lower Donna River and possibly all the way north to the Arctic Coast, deposition continued without interruption or almost so throughout this time interval. The episode is, however, reflected even there by the presence of the non-marine components of the white sandstone member of the Lower Sandstone Division, and the lower member of the Coal-bearing Division" (latter is absent in Stony Creek area). Continental deposition associated with uplift in the southern part of the Richardson Mountains lasted from Middle Valanginian to late Upper Hauterivian. The arkosic composition and coarse grain size of the white sandstone member lithologies indicate the influence

of a major uplift to the south. Then the mid-Lower Cretaceous sea flooded the region once more forming a long narrow embayment extending from the northern Richardson Mountains southward to the lower Peel River (Fig. 3). Jeletzky (1958) notes that all known or suspected marine deposits of this age are within this embayment. This structural trough is believed to be the same one that was occupied by the early Lower Cretaceous sea. The sea entered the basin from the northwest with facies changes in a north-south direction for the mid-Lower Cretaceous rocks (Upper Shale-Siltstone Division and Upper Sandstone Division).

The mid-Lower Cretaceous transgression is reflected in the lithologic differences between the lower and upper members of the Coal-bearing Division in the northern part of the area (Donna River). The transgression spread rapidly southward beyond the Stony Creek area during deposition of the Upper Shale-Siltstone Division. In the Stony Creek-Vittrekwa River area the Upper Shale-Siltstone Division undergoes a facies change to arenaceous equivalents caused by proximity to the mid-Lower Cretaceous shoreline at this time. Widespread transgression of the mid-Lower Cretaceous sea is responsible for major overlap of older rocks by the Upper Shale-Siltstone Division. A minor regression during deposition of the lower member of the Upper Sandstone Division would account for the more arenaceous nature of this shallow water facies. Unlike that of the Lower Sandstone Division, this regression was short lived. Overlap on the underlying lower member and on older Paleozoic rocks by the upper (grey sandy siltstone) member indicates a

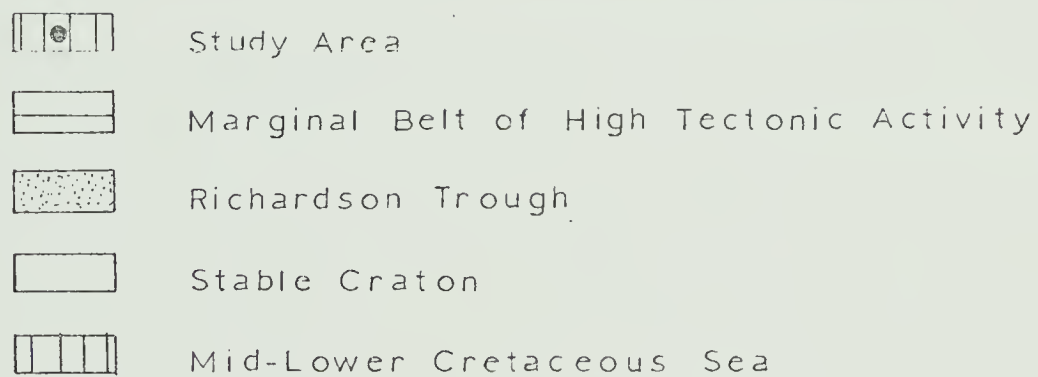
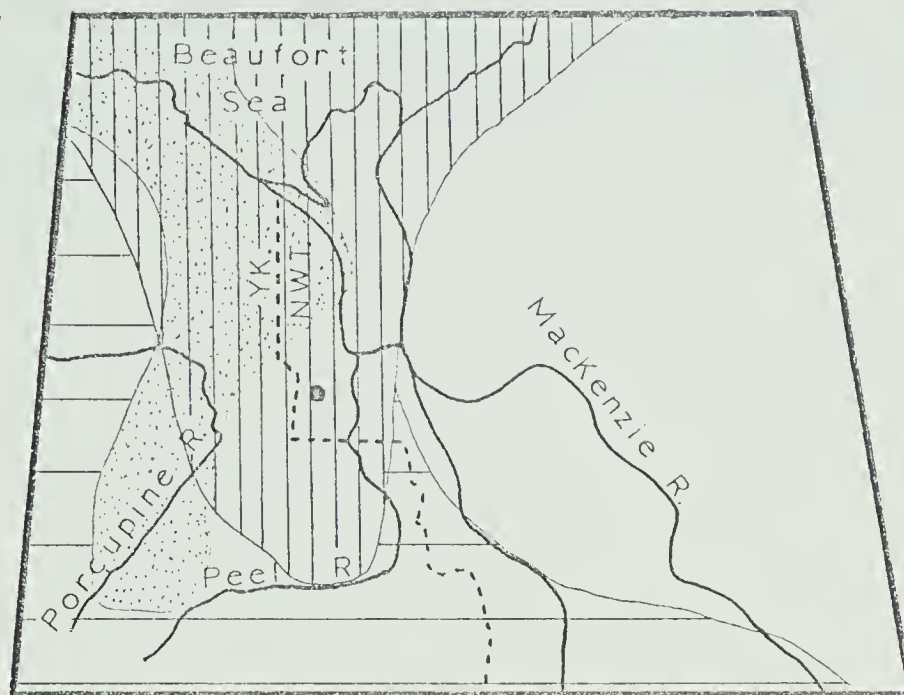


Figure 3: Extent of mid-Lower Cretaceous sea

*adapted from Martin (1959)
and Jeletzky (1958)

further advance of the mid-Lower Cretaceous sea during late Upper Aptian time. Deposits representing the following major regression of the mid-Lower Cretaceous sea are missing at an erosional unconformity. This erosional period is followed by the Clearwater Sea transgression of Early to Middle Albian and deposition of the overlying Albian Shale-Siltstone Division.

UPPER SANDSTONE DIVISION

General mineralogy

The sandstones of the Upper Sandstone Division are light grey to buff in color. Examination of the components shows a wide range of compositions as follows: 22 to 86 per cent quartz, trace to 18 per cent feldspar (includes both potash feldspar and plagioclase), 1 to 70 per cent chert, 0 to 25 per cent rock fragments (clay rock fragments generally less than 10 per cent with the higher percentages associated with chloritized clay lithoclasts), 0 to 17 per cent calcite, 0 to 45 per cent siderite, trace to 26 per cent matrix (usually illitic although sometimes chloritic-illitic), trace to 10 per cent glauconite, trace to 15 per cent chlorite (as cement), 0 to 7 per cent chamosite pellets, 0 to 5 per cent pyrite, 0 to 4 per cent muscovite, 0 to 3 per cent kaolinite, 0 to 11 per cent limonite or hematite, 0 to 1 per cent dolomite rhombs, 0 to 1 per cent heavy minerals (zircon, tourmaline, epidote), and 0 to 5 per cent organic matter.

On the basis of composition the sandstones can be classified into six mineral-facies. These are: quartz, quartz-chert, quartz-carbonate-glauconite, quartz-chlorite, and two less important facies, quartz-feldspar and quartz-matrix or argillaceous sandstones. In the F52A and F42 wells the quartz facies predominates followed by the quartz-chert facies with carbonate cement content negligible.

Authigenic minerals

The term authigenic minerals will apply collectively to those minerals which have formed after the sediment was deposited. This includes mineral growth occurring before, during, or after lithification and represented by new growths in pore spaces (chemical cements), and within other minerals (replacement).

The common secondary or authigenic minerals occurring in the sands of the Upper Sandstone Division are: quartz, calcite, siderite, kaolinite, glauconite, chamosite, chlorite, hydrous oxides, pyrite, sericite, muscovite, albite, dolomite, and hematite. Where feasible, each authigenic mineral is considered in terms of microscopic attributes, mode of origin and time of formation.

Quartz:

Secondary overgrowths on detrital quartz grains were observed in all thin sections examined and varied from trace amounts to 6 per cent. Quartz enlargements are in optical continuity with the detrital core, and can be recognized in thin section only if there is a dusty zone of inclusions marking the original surface of the detrital grain. In sandstones having abundant carbonate cement or matrix the quartz rims are very small or lacking altogether. In the cleaner sandstones overgrowths are well developed and characterized by a "feathery" nature (partial euhedral crystal growth), rather than uniform rims (Plate I-1 and II-1). In a few rare occurrences, the secondary quartz appears to have the form of granular aggregates between detrital grains. There is no critical grain size for the precipitation of quartz overgrowths. In

the majority of cases overgrowths are confined to pore spaces although in argillaceous sandstones the quartz rims seem to grow into the matrix.

A number of modes of origin have been suggested for the silica involved in quartz enlargements. Waldschmidt (1941) believed that quartz dissolving along grain contacts due to pressure solution was the source for most of the silica cement in many sandstones of the Rocky Mountain region. The same conclusion was reached by Gilbert (1949) and Siever (1959). However, pressure solution can not satisfactorily account for silica overgrowths in the Upper Sandstone Division as suturing is distinctly lacking. Lerbekmo (1961) said that failure to differentiate nucleus and overgrowth has led to the reporting of pressure solution contacts between quartz grains when in fact the contacts are simply growth contacts. Fothergill (1955), Greensmith (1957), and Walker (1960), attributed overgrowths to local enrichment of intrastratal water in silica in zones associated with extensive decomposition of feldspar, with precipitation of silica immediately or at a later date. Goldstein (1948) attributed his secondary enlargement of quartz grains to solution of fine quartz particles and possibly to some degree to derivation from outside sources. Most writers thought that deposition of silica from circulating connate or meteoric waters was most unlikely. Siever (1959) also postulated a source for silica overgrowths from diatoms, but acknowledges that there is generally too much silica cement present to be accounted for by this process alone. Kryniene (1941) was a strong advocate of secondary silica being penecontemporaneous with the deposition of the sand. He attributed this to a superabundance of dissolved silica

in sea water and to conditions favorable for its precipitation. He stated, "Probably close to 95 per cent of the secondary silica in the Oriskany (and in many if not most other quartzites and cherts) is really of primary penecontemporaneous sedimentary origin. Not over 5 per cent of secondary silica in the Oriskany can be indisputably assigned to later silicification from circulating solutions." Teodorovich (1961)

considered authigenic quartz as the product of recrystallization of opal and other minerals of the chalcedony group, and sometimes of precipitation from weakly mineralized fluids during their slow advance. For the Upper Sandstone Division sandstones, an early diagenetic origin is indicated with perhaps minor contributions from silica released by carbonate replacement of silicates. Secondary silica, in many cases, occurs very early in the diagenetic history before compactive stresses were effective. This is reflected in the fact that most quartz grain contacts are growth contacts. Greensmith (1957) found a similar situation in the Upper Carboniferous Sandstones in Northern Derbyshire, England as did Adams (1964) in the Lower Morrow sandstones. On the other hand, Heald (1950 and 1956), and Heald and Anderegg (1960) found authigenic quartz to occur after compaction of the sediment. This means that the origin of the silica is probably related to its time of precipitation. Overgrowths before compactive stresses would have to be near penecontemporaneous while those sandstones showing pressure effects before overgrowth development could have pressure solution providing the source of the silica.

Siderite:

Siderite is present in some of the thin sections as the predominant carbonate mineral in both primary and secondary forms. The primary siderite occurs in three forms: microgranular, very fine sand sized rhombohedra, and microspherulites and is associated with smaller amounts of organic matter. Where siderite occurs in its replacement form it is as rhombic euhedra or as spherulitic grains. The replacement siderite is very minor in the small number of slides in which it occurs as a replacement product of chamosite. Wherever the siderite occurs as a primary cement the clastic grains appear to be "floating" in a siderite cement. The very fine grained rhombohedra are considerably cleaner in appearance under plane polarized light than the surrounding siderite cement. Excellent siderite spherulites are developed in some of the shell debris (Plate I-2).

It is felt that the carbonate has been furnished to a large extent by fossil shells which are usually fairly abundant in the calcareous portions of the Upper Sandstone Division. In the presence of organic matter, the carbonic acid-charged waters probably furnished the less common siderite cement over the usual calcite cement. In addition, some siderite is seen to be an alteration product of biotite with good intermediate stages being visible.

Deposition of the siderite cement must have been penecontemporaneous with deposition in order to account for the very loose packing and hence for the "floating" nature of the original detrital grains. Lerbekmo (1961) and Adams (1964) found carbonate cementation at an early stage in the diagenetic history with sand grains floating in a carbonate

cement as indicative of cementation prior to appreciable compaction.

Calcite:

Calcite is present in a few of the specimens studied. It occurs in two different roles: primary pore filling and secondary replacement calcite. The relative amounts of primary and secondary calcite could not be precisely determined in most cases. When calcite occurs as a pore filler it has sharp boundaries visible under plane polarized light and is relatively free of impurities (Plate I-3, I-4). It sometimes occurs as large crystals encompassing several detrital grains. The clear pore filling calcite is usually associated with the cleaner sandstones in contrast to the replacement calcite which occurs in the cleaner sandstones as well as in those containing fairly abundant clay.

Most authors (Krynine, 1941; Heald, 1950; Lerbekmo, 1961; and Adams, 1964) attribute most calcite cement to solution and reprecipitation of calcareous material originally present in the rocks. Such is probably also the case for the Upper Sandstone Division which has numerous fossil zones scattered throughout its thickness. The isolated patchy distribution of calcite is ascribed to redistribution of the calcite by circulating ground waters (Greensmith, 1957). The latter explanation is generally accepted for patchy calcite distribution but for "floating" grains most authors assume a penecontemporaneous origin. However, Waldschmidt (1941) found it difficult to visualize conditions under which the sand grains could be so evenly distributed if the calcite is of penecontemporaneous origin. He stated, "It seems more logical to assume the deposition of a sand composed of a large per cent of calcareous

fossil fragments and a small per cent of quartz grains. The distribution of the constituent grains would then be uniform because of mechanical mixing. Consolidation of the mass could be accomplished by solution of the calcareous fossil fragments before appreciable migration of the saturating water." In this way, one could attribute both the patchy calcite distribution and the calcite "matrix" to the same mode of origin and mechanism of distribution. All floating quartz grains in the Upper Sandstone Division are associated with the siderite cement. Calcite generally does not exceed 15-20 per cent of a rock in contrast to siderite cement which constitutes 30-50 per cent of some of the thin sections. The calcite cement was precipitated early in the diagenetic history of these sandstones, usually prior to any appreciable compaction. Calcite replacement, on the other hand, may have occurred at any time later.

Glauconite:

Glauconite is present in most of the thin sections studied but more commonly occurs where carbonate cement is fairly abundant. It is recognized by its green color, lobate grain form, and microaggregate extinction. In some instances it appears to be interstitial (Plate III-2), but usually has the form of pellets. Normally, the glauconite pellets show smooth outlines although some shrinkage cracks are occasionally observed (Plate I-5, I-6). The glauconite occurs where it shows no genetic relationship to other minerals. For this reason, according to Light (1952), the glauconite would be detrital. The author, however, is not in agreement and feels the glauconite pellets are authigenic in origin.

At least three major origins for glauconite formation have been postulated. Burst (1958) favors large chemical changes in the basic lattice and interlayer cations of the predominantly illite-montmorillonite clays that occur as glauconite pellets. Galliher (1935) showed glauconite originating from altered biotite, observing the intermediate stages from biotite to altered biotite to glauconite. Teodorovich (1961) considered glauconite as precipitating from sea water as a coagulated gel and that all marine glauconite forms from colloidal solutions. The present author favors colloidal solutions as responsible for the glauconite formation of the Upper Sandstone Division, primarily because of the lack of obvious genetic relationship to the other minerals. Glauconite commonly forms where bottom currents are strong and sedimentation retarded or temporarily reversed. Consequently, it should not be unusual to find smooth glauconite grains and glauconite with shrinkage cracks together, both of the same origin. The glauconite grains often show alteration which reflects glauconite sensitivity to the oxidation-reduction boundary. Where associated with abundant carbonate cement the surfaces of glauconite grains are found corroded indicating the presence of glauconite before cementation. In some cases, where the glauconite has developed an iron oxide rim, it is generally not affected by carbonate replacement.

Chamosite:

Chamosite is present in only a few of the thin sections and is found where the glauconite content is relatively high and carbonate cement abundant. It is pelleted in form with irregular boundaries and

surrounded by iron oxide rims. The chamosite is characterized by a pale greenish-yellow color which is weakly pleochroic and has a microscopic scaly appearance. Under crossed nicols it is nearly isotropic (Plate I-7, I-8).

Very little seems to be known about the origin of chamosite. Like glauconite, it may form from coagulated gels. Its characteristic pelleted form and lack of apparent genetic relationship to other minerals suggests that it is formed penecontemporaneously with the glauconite. Porrenga (1966) states, "It is difficult to trace the diagenetic history of chamosite since it does not contain interlayer water and is not expandable. The possibility exists that chemical analysis will permit distinction to be made between intermediate stages in the diagenetic development of chamosite."

Chlorite:

A pale green mineral, having an acicular structure and believed to be chlorite, is present in many of the sandstones of the Upper Sandstone Division. The distribution is rather irregular even within a single well. The authigenic chlorite occurs as thin scaly fringes, particularly around the quartz grains (Plate II-2, II-3), where it has grown on quartz enlargements as well as between the overgrowth and detrital core. The distribution of chlorite on the quartz enlargements is random and is not particularly confined to surfaces facing voids. This is in contrast to the findings of Heald (1950) who considered chlorite authigenic because it occurred only on surfaces of grains facing voids and not between grains. In sands of the Upper Sandstone Division the chlorite is often

found between a quartz grain with an overgrowth and one without an overgrowth. The authigenic chlorite was introduced fairly early in the diagenetic history, both before and after quartz overgrowths but before compactive stresses became effective.

The chlorite originated from circulating solutions of connate or meteoric water. This is reflected in the often patchy or erratic distribution. Chlorite also occurs as "pellets", although these are thought to be of detrital origin rather than penecontemporaneous with the glauconite or chamosite. The "pellets" by and large, are attributed to chloritic alteration of clay rock fragments as a result of halmyrolysis.

Hydrous oxides:

Iron oxide, with the light orange color common to hydrous varieties, occurs in a large number of the slides. Even under high magnification, however, it is difficult to detect the discrete particles of ferruginous material. The iron oxide is associated primarily with the siderite, glauconite, chamosite, organic matter, and pyrite (Plate I-2, I-7, III-4), where it occurs as rims.

Because of this association with the above ferrous iron-bearing minerals the iron oxide is likely to be of secondary origin resulting from their alteration. Goldstein (1948) stated, "Most ferruginous material is either deposited concurrently with the detrital particles, or is carried in by percolating ground waters before induration is complete." Regardless of whether the iron oxide is primary or secondary, there is no doubt that some redistribution of this material has taken place. For this reason, it is not feasible to separate primary and

secondary ferruginous material quantitatively. It must be acknowledged, however, that iron oxides are significant in the diagenetic history of these sandstones.

Hematite:

Dark reddish hematite occurs in small amounts, particularly in those thin sections where siderite cement is abundant. It occurs as scattered grains throughout the cementing medium. Swineford (1947) has suggested that most of these types of grains are probably pseudomorphs after pyrite or rhombohedral siderite crystals (Plate II-4). This is difficult to determine in the Upper Sandstone Division sediments. Here the hematite content in places reaches as high as four per cent.

Pyrite:

Pyrite is present in small amounts in most of the samples. It has the form of anhedral grains or well developed small euhedral crystals. They generally occur in small clusters and only rarely enclose any detrital grains. Pyrite occurs as an interstitial filling and a replacement of chlorite rims or clay matrix (Plate II-5). Formation of pyrite definitely occurred during the late stages of diagenesis, as it replaces many of the earlier authigenic minerals.

Dolomite:

Trace amounts of secondary dolomite are present in only a few thin sections. The dolomite has its characteristic rhombohedral shape and occurs as a replacement of siderite or calcite cement and chert grains (Plate III-1). Its paragenetic relationship to the other authigenic minerals could not be determined because of its relative insignificance.

Feldspar:

Authigenic feldspar is found in very minor amounts. The potash feldspar generally does not show secondary enlargement. Feldspar overgrowths which are untwinned, water clear, and in partial optical continuity with the core (Plate II-5) occur on albite grains.

Time of feldspar overgrowth formation is generally late in the diagenetic history as all silica-laden waters would favor precipitation of silica as quartz overgrowths over feldspar overgrowths during early diagenesis (Dapples, 1967).

Sericite:

Sericite is prevalent in most specimens and particularly in those bearing substantial amounts of feldspar. Under reflected light, sericitic replacement renders grains a greyish-white color, and produces, in many cases, a pseudofibrous texture. In these clouded grains, a type of aggregate polarization can generally be noted. Sericite formation is an alteration product of silicates, and feldspar and quartz are the predominant minerals affected. It is an intermediate product during the conversion of feldspars to kaolinite. Most of the sericite is probably pre-deposition. This conclusion is based on the association of fresh and weathered potash feldspar or plagioclase within the same sample.

Hydromuscovite-Illite:

Hydromuscovite is present in very minor amounts in most of the thin sections studied. It is characterized by thin, colorless, platy grains having strong birefringence. Authigenic hydromuscovite develops during

the later stages of diagenesis from alteration of clay minerals. There is a direct relationship between the amount of muscovite and the amount of clay in these quartzose sandstones (Plate III-1).

Other clays:

Although secondary clays, other than chlorite and hydromuscovite-illite play a very minor volumetric part in the sandstones of the Upper Sandstone Division, their role in diagenesis warrants closer examination. Lerbekmo (1961) points out that diagenetic precipitation of clay in sandstone pores is readily misinterpreted as a primary feature of sedimentation. Both Lerbekmo (1961) and Carrigy and Mellon (1964) have found authigenic clay mineral cements to be of considerable importance in the Cretaceous and Cretaceous-Tertiary rocks, respectively, of Alberta. In contrast, Weaver (1958) states, "It is concluded that the great majority of clay minerals in sedimentary rocks are detrital in origin, strongly reflect the character of their source material, and are only slightly modified in their deposition environment." Weaver feels that cation adsorption is the most common process acting on clay minerals in the marine environment. Because there is no change in the basic clay mineral lattice for many of these reactions he does not consider them as part of diagenesis. Weaver (1959) conceded that considerable local variation in marine clay suites has been attributed to syngenetic alterations of the detrital clay minerals, but was reluctant to postulate authigenic clays as deposited from circulating solutions as does Carrigy and Mellon (1964) or Lerbekmo (1961). The present writer views the evidence in the Upper Sandstone Division as

favouring processes of clay mineral diagenesis. Chlorite, formed authigenically, should form the bulk of a clay mineral suite, as it does in the Upper Sandstone Division. X-ray diffraction work shows adjacent shales to consist predominantly of illitic material with minor chlorite and/or kaolinite. Further work to attempt to differentiate between the latter two minerals in the shales was not undertaken, but petrographic examination of the sandstones shows dominantly a chlorite rather than kaolinite content. Therefore an illite-chlorite composition for the adjacent shales is considered likely, with chloritic material in the sandstones being formed by solutions expelled from the surrounding shales. Weaver (1959) also mentions that in most instances it appears that the clean, more quartzose sandstones are more apt to contain secondary kaolinite. This, however, is rare for the Upper Sandstone Division sediments. There does not appear to be any relationship between clay mineral suites (which are very minor in this study) and environment for the Upper Sandstone sediments.

Authigenic kaolinite is the only secondary clay (excluding chlorite) formed in these sandstones and it is present in amounts generally less than five per cent. The kaolinite is characterized by a clean mosaic-like aggregate. Some of the kaolinite fills pore spaces (Plate II-7), but much of it is partially altered feldspar. The presence of fresh and weathered feldspar together argues against the concept of post-depositional kaolinization of feldspar; rather the kaolinization is attributed to differential weathering in the source area. There also appears to be some kaolinite formed as a result of illite-chlorite alteration, although this may be chlorite.

Murray and Sayyab (1955) found that diagenetic changes appear in the form of changes in the crystallinity of clay minerals rather than changes in basic clay mineral type. Some of the clay rock fragments of the Upper Sandstone Division show such recrystallization, but others have become chloritized.

In conclusion, clay mineral diagenesis seems to be more important than some authors wish to admit. Keller (1963) realized this in his review of diagenesis in clays. Clay mineral diagenesis, he states, should occur if: a) there are adequate amounts of those elements that are incorporated within the clay mineral, b) that the combining ion is accompanied by energy of sufficient intensity to activate the reaction, and c) that there is sufficient geologic time if energy intensities are low or availability slow.

Miscellaneous:

In addition to those authigenic minerals already described, one other may be noteworthy. The chert cement (Plate II-7, II-8) which occurs as overgrowths on chert grains appears only twice (C2 well) with quantities up to six per cent.

Sequence of formation

The sequence of formation of the secondary minerals differs slightly in most of the specimens studied. The earliest minerals to form are glauconite and chamosite because of their penecontemporaneous origin. The second step in authigenic mineral growth may be any one of the following: a) there may be quartz overgrowths on detrital cores. This is particularly prevalent in the C2 well from 462 feet

through to 568 feet, b) there may be development of chlorite rims or sometimes other clay rims on the detrital core before the crystallization of quartz overgrowths. These chlorite rims are fairly uniform in thickness and generally show complete envelopes. Where this occurs, quartz overgrowths are rather incomplete and sparsely distributed. This second possibility is the one particularly prevalent throughout much of the F42 well, c) uniform and very complete chlorite rims may form on detrital quartz cores before the introduction of carbonate cement. Here quartz overgrowths are rare in occurrence. This pattern is abundant in the F52A well from 580 feet to 668 feet and in the C2 well from 60 feet to 102 feet, with only one occurrence in the F42 well at 327 feet.

The third step in authigenic mineral growth is deposition of the carbonates, siderite and calcite. The order of these two carbonates could not be established. Calcite and siderite cement are sometimes later than quartz overgrowths or chlorite cement but may be earlier where the latter two are absent. This is particularly true of the siderite cement. The calcite cement usually occurs after quartz overgrowth development. Where chlorite rims occur without the presence of quartz overgrowths the siderite cement is in contact with these chlorite rims.

The fourth step in authigenic mineral growth involves dolomite, hydromuscovite, hematite, pyrite, or hydrous oxides. The dolomite may have originated at any time after the precipitation of the other chemical cements. Dolomite rhombs occur replacing calcite cement and particularly chert grains. Hydromuscovite forms in part from the recrystallization of clay minerals. Pyrite and hematite are found

replacing hydromuscovite. The hydrous oxides have a fairly wide time range. Where they are associated with glauconite or chamosite, the hydrous oxides occur before carbonate cementation, but they also occur as alteration products of pyrite.

The remaining three authigenic minerals are even more difficult to evaluate. The chert cement shows no obvious time relationship to any of the other authigenic minerals. The feldspar overgrowths are assumed to have formed sometime during the late stages of diagenesis as silica deposition would probably favor quartz overgrowths instead of feldspar overgrowths during early stages of diagenesis. Due to their rare occurrence, insufficient evidence was obtained. Lack of good petrographic evidence makes the position of kaolinite difficult to assess within the diagenetic history of these sandstones. Greensmith (1957) mentions that the general absence of authigenic quartz growth where kaolinite pockets are adjacent to quartz grains indicates the co-deposition of clastic grains and the kaolinite. On the other hand, kaolinite may also be the last authigenic mineral to crystallize. It may simply fill interstices left after the growth of the other secondary minerals. Based on the limited petrographic evidence in the Upper Sandstone Division either a very early or a very late paragenetic relationship would be possible.

Porosity and packing

In the sandstones of the Upper Sandstone Division it has been found that low porosities are due in part to sorting but primarily to diagenetic changes. Taylor (1950) listed three factors responsible for pore space reduction: 1) simple pore filling, 2) solid flow of material under pressure, 3) solution and redeposition. The first factor simply involves the deposition of authigenic minerals in voids between sand grains. The first process does not alter the shape of the grains in any way and accounts, therefore, for reduced porosity without compaction. Carbonate cement is the most effective pore filler, in the Upper Sandstone Division. However, porosity is still relatively high (8-10 per cent) in some of the samples and is attributed to solution of carbonate cement. Quartz overgrowths and hydromuscovite are not very important as pore filling cements. However, where porosities are relatively high, the hydromuscovite content is generally minimal.

Simple pore filling is usually indicated by the type of grain to grain contact. "Floating", tangential, and long contacts are all associated with simple pore filling (Taylor, 1950), (Plate III-6). The former two result from packing whereas the latter has been attributed to precipitated cement and minor pressure as well as packing (Taylor, 1950). The second factor involves solid flow without solution and/or redeposition. Taylor stated that the best evidence for solid flow of material under pressure is provided by rock fragments of heterogeneous composition which conform to grains with which they are associated forming a contact which preserves the outline of the non-yielding grain. Solid flow is the most important feature illustrated in the Upper

Sandstone Division. Solid flow features are usually identified by concavo-convex grain contacts. Clay rock fragments, and in many cases glauconite pellets, are the lithoclasts which best illustrate this type of contact (Plate III-7, III-8). This feature is, however, not confined to rock fragments but also occurs at contacts between quartz and chert grains. Where the concavo-convex contacts are associated with quartz grains there is no concentration of silica, indicating a lack of chemical activity. Taylor (1950) states, "The chemical composition of the yielding grains does not seem to be the controlling factor in the development of concavo-convex contacts".

The third factor involves solution and redeposition under pressure and is more commonly referred to simply as pressure solution. Strong pressure solution, marked by suture-like penetrations or crenulations, is minimal in sands of the Upper Sandstone Division. In the one or two instances where it occurs, pressure solution is confined to chert-rich zones (Plate II-8, III-3).

From Table 2, it may be seen that porosity is related to the abundance of clay rock fragments, quartz framework grains, and chert rock fragments in these Upper Sandstone sediments. High porosities have been arbitrarily chosen as those porosities between 6 and 17 per cent. Where the clay rock fragment quantity is high, porosities appear to be the greatest, and the quantity of chemical cement low. (Three exceptions occur: at F52A-570, F52A-580, and F42-312 where both porosity and carbonate cement content are high; the porosity here has been attributed to solution on the basis of pore space outlines.) The relationship of porosity and clay rock fragments would imply that the

presence of clay rock fragments, in both squeezed and unsqueezed forms must be inhibiting the precipitation of chemical cement. The occurrence of both squeezed and unsqueezed forms is related to the proportion of quartz or framework grains which resist overburden pressures. Where clay rock fragment content is low, porosity may still occur because of the lack of any true matrix within the framework grains. In the C2 well, the occurrence of abundant chert has much the same effect as the more abundant quartz framework grains in preventing the clay rock fragments from being "drawn out" into a paste. Some of the highest porosities occur in this association.

Taylor (1950) had pointed out that solid flow is the most important factor in porosity reduction. Because of shallow depth, pressures have not been great enough to completely squeeze the clay rock fragments into a "paste". It appears that these undistorted to minor distorted clay rock fragments inhibit the precipitation of chemical cements. Simple pore filling is the greatest factor in porosity reduction where the clay rock fragment or chert content is low. Pressure solution has been least effective in reducing pore space because evidence of suturing between quartz grains is distinctly lacking.

TABLE 2

Samples showing relationships between porosity, chemical cements, and mineralogy .

Well	Por.	Carb.	O/g	Chl.	Clay RF	Chert	Quartz
F52A-570	7	45	2	-	9	-	22
-580	8	30	tr	12	tr	2	44
-600	2	24	tr	15	4+	2	48
-620	6	tr	2	11	16	1	71
-628	9	tr	3	9	11+	1	69
-850	8	1	1	2	14	1	72
-869	3	2	6	3	5	2	76
-880	5	1	2	1	4+	2	73
-890	8	1	4	3	9	2	70
-900	tr	tr	1	-	12+	1	86
-910	6	-	4	3	11+	23	56
-920	6	2	1	-	6	2	75
-925	tr	40	tr	-	4	-	51
-930	-	1	1	13	26	9	62
-944	1	17	3	-	10	3	64
-950	4	tr	2	-	10	3	72
F42 -312	9	35	tr	-	11	1	21
-327	5	31	tr	-	2	1	43
-335	3	1	5	4	23+	1	57
-350	8	-	4	3	11+	1	66
-365	1	tr	2	1	12+	tr	71
-377	3	1	2	1	22	-	43
-396	-	tr	3	-	11+	tr	52
-585	7	1	3	-	7	-	81
-595	7	7	6	-	11	1	71
-610	4	1	3	-	8	1	79
-625	6	1	3	-	11+	1	76
-635	4	2	2	-	6+	1	75
-644	-	17	1	-	6+	-	70
-648	7	tr	4	-	11	2	71
-665	11	4	3	-	18	9	63
-679	8	1	3	-	11	5	72
-683	-	1	4	-	15	1	58
-955	10	-	4	-	10	4	75
-970	13	-	3	-	6+	5	67
-980	tr	12	4	-	10	6	66
-985	tr	15	2	-	5+	4	40

TABLE 2 (con'd)

Well	Por.	Carb.	O/g	Chl.	Clay RF*	Chert	Quartz
C2 -31	8	-	2	4	25	1	53
-50	13	1	3	11	17	1	59
-68	10	tr	2	6	8	tr	59
-275	10	tr	5	-	2	3	75
-285	6	3	1	-	2	80	25
-290	13	1	2	-	2	2	77
-305	6	1	2	-	6+	tr	74
-310	13	1	4	3	6	4	70
-435	4	tr	3	-	22	15	49
-462	11	2	2	-	20	35	39
-475	10	2	4	-	12	30	36
-501	17	tr	5	-	6	15	53
-533	2	-	5	-	4	29	53

Clay RF* is the sum of clay rock fragments and "matrix" which is believed to be squeezed clay rock fragments judging from its irregular distribution.

Por. = porosity
 Carb. = carbonate cement (calcite and siderite)
 O/g = quartz overgrowths
 Chl. = chlorite

Patterns of cementation

Siever (1959) pointed out that variations in the degree of cementation may be due to a number of characteristics. Patterns in cementation may be related to structural history and attitude, or original sedimentation conditions, or modal mineralogy, or depth of burial or the chemical nature of the circulating connate or meteoric solutions.

In the Upper Sandstone Division, variations in the degree of cementation have been attributed mainly to changes in mineralogy. From Table 2, it may be argued that the significant porosity changes within each sandstone zone and the well as a whole could not be due to structural history or depth of burial. Such localized variations could only be caused by something inherent in the sands at particular stratigraphic positions. It was decided to examine a number of parameters to see if there were any existing relationships. The following points were observed: 1) there is no noticeable relationship between type of cement and depth; 2) as all depth differences are less than 1000 feet, packing differences were ineffective in determining porosity differences; 3) in general, sorting was not especially important. Only where poor sorting extended far enough into the fines to provide a distinct matrix was the observable or effective porosity substantially reduced; 4) grain contact changes over the depth interval studied are not very effective in delineating increase in pressure; 5) quartz overgrowths are distinctly minor where sandstones are chert-rich. Deposition of silica is preferentially induced by a monocrystalline quartz grain because of the single optical orientation (Sloss and Feray, 1948).

Variations in the degree of cementation are related not only to the porosity of a sediment, but, more important, to the permeability. The variations are related to the type and amount of cementing material. Generally, those sediments that were the most permeable are now the most lithified.

Patterns of cementation are the result of four mineral cements (calcite, siderite, chlorite, and quartz) and three mineralogical components (clay rock fragments, chert rock fragments, and quartz framework grains). The irregular distribution of cements and porosities is due to the relationship between chemical cements and clay rock fragments.

In conclusion, it appears that lack of cementation and consequent preservation of porosity is most favorable in four types of lithologies or their combination. These are: 1) chert-rich sandstones at shallow depths; 2) quartz sandstones with chlorite-coated quartz grains; 3) an essentially matrix-free quartzose sandstone; 4) quartz sandstones with an abundance of clay rock fragments.

PLATE I

Thin Section Photomicrographs

1. Authigenic silica overgrowth on a rounded quartz grain. (F42, depth 955 feet), crossed nicols, 64X.
2. Spherulitic siderite developed in pelecypod shell fragment found in a siderite cement (upper right). Note also abundant iron oxide rims. (F42, depth 312 feet), crossed nicols, 40X.
3. Chlorite rims (dark areas surrounding quartz grains) in a carbonate cement. Note lack of carbonate replacement of quartz because of protective chlorite rims. (F52A, depth 600 feet), crossed nicols, 32X.
4. Discontinuous patches of carbonate cement (speckled medium grey). (F42, depth 985 feet), crossed nicols, 25X.
5. Glauconite pellets (mottled appearance). (F42, depth 880 feet), crossed nicols, 13X.
6. Distorted glauconite pellets (mottled appearance) with chert (dark grey, very fine pin-point) and quartz. (F42, depth 913 feet), crossed nicols, 25X.
7. Chamosite pellets (mottled appearance) with iron oxide rims in a siderite cement. (F42, depth 312 feet), plane light, 16X.
8. Chamosite pellets in a siderite cement. (F52A, depth 570 feet), plane light, 40X.

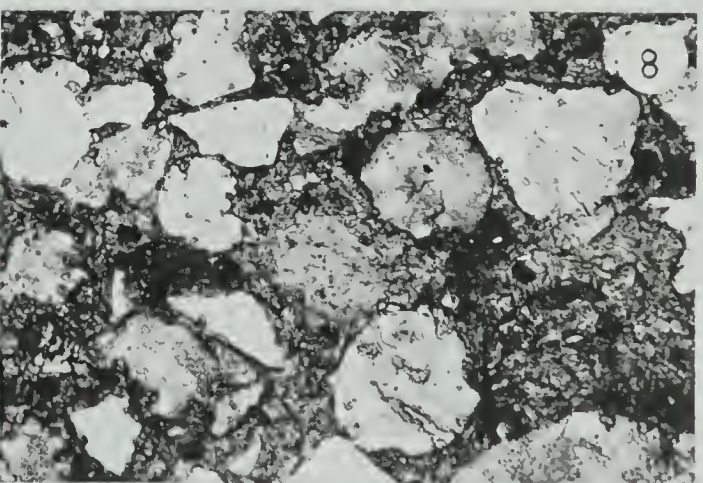
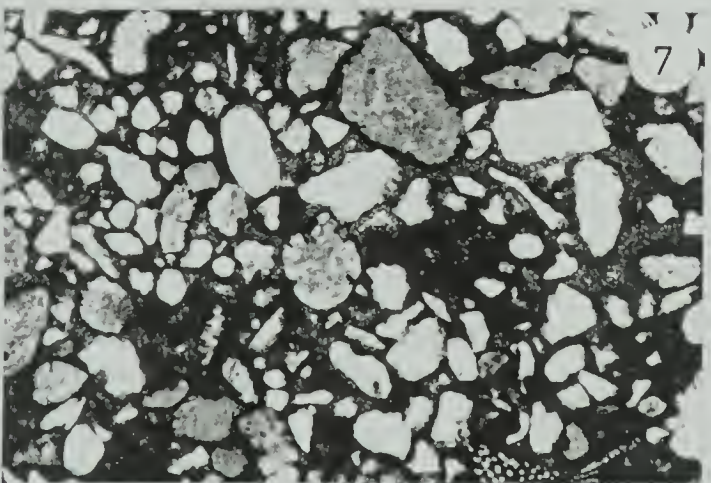
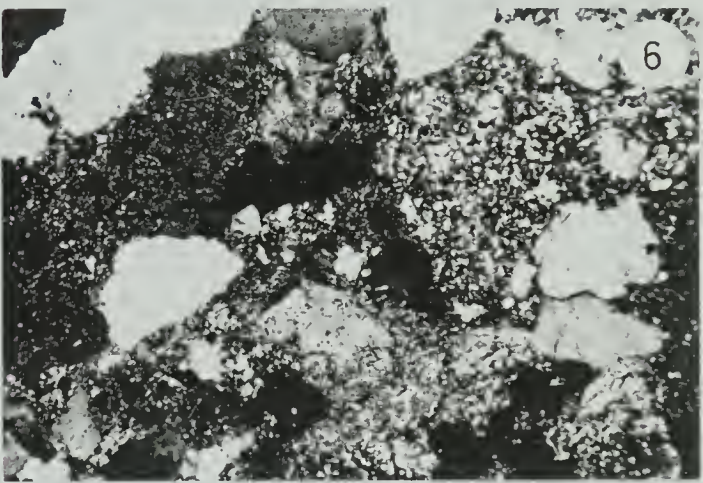
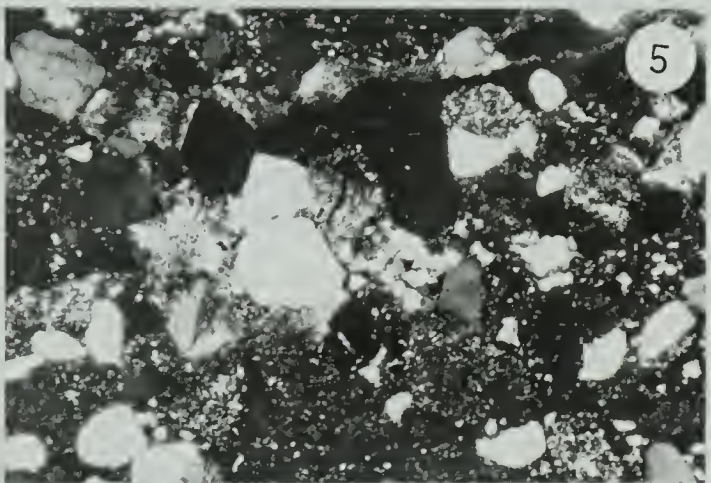
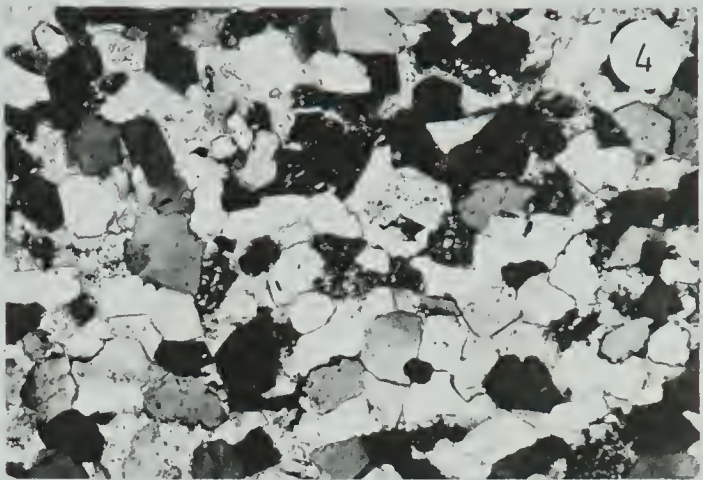
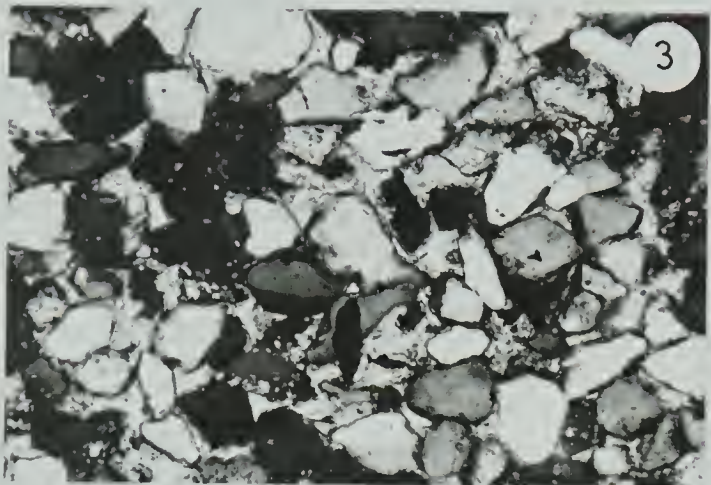
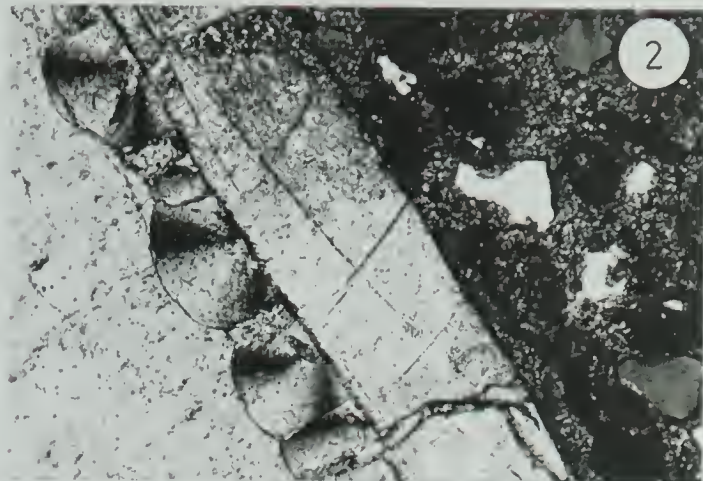
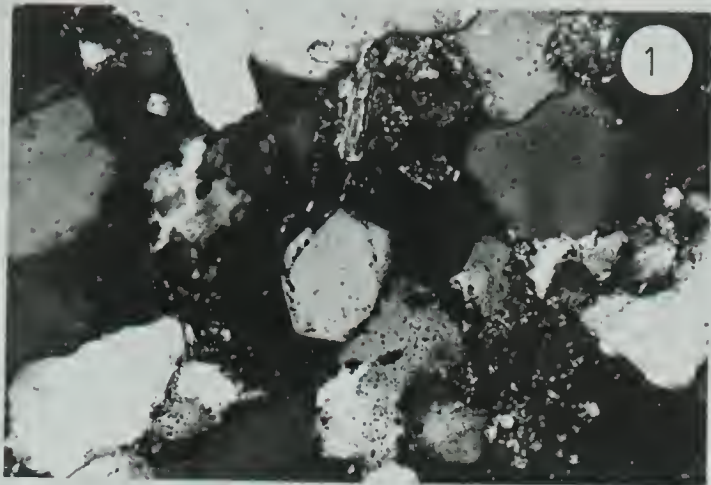


PLATE I

PLATE II

Thin Section Photomicrographs

1. Two stages of authigenic silica overgrowth. Note also chalcedony grain welded to the overgrowth. (F52A, depth 910 feet), crossed nicols, 125X.
2. Well developed chlorite rims between the overgrowth and the quartz core. Note resistance to overburden pressures because of "cushioning" affect of the chlorite cement. (F52A, depth 555 feet), plane light, 32X.
3. Chlorite rims and chloritic matrix (chloritized clay lithoclasts). (F42, depth 335 feet), plane light, 32X.
4. Hematite blebs (bottom, central) in a carbonate cement. Note corrosion of quartz grain boundaries by the carbonate cement, and minor secondary porosity (upper left); also "floating" nature of the quartz grains. (F42, depth 327 feet), crossed nicols, 82X.
5. Authigenic feldspar overgrowth and quartz overgrowths. (F42, depth 258 feet), crossed nicols, 102X.
6. Pyrite replacement, particularly confined to clay lithoclasts or chlorite rims. (C2, depth 50 feet), plane light, 40X.
7. Chert cement (mottled appearance) with very minor kaolinite cement (indistinguishable in photo). (C2, depth 533 feet), crossed nicols, 32X.
8. Chert cement with carbonate cement and carbonate cement replacement. Note lack of definite shape to the chert grains. (F42, depth 990 feet), crossed nicols, 10X.

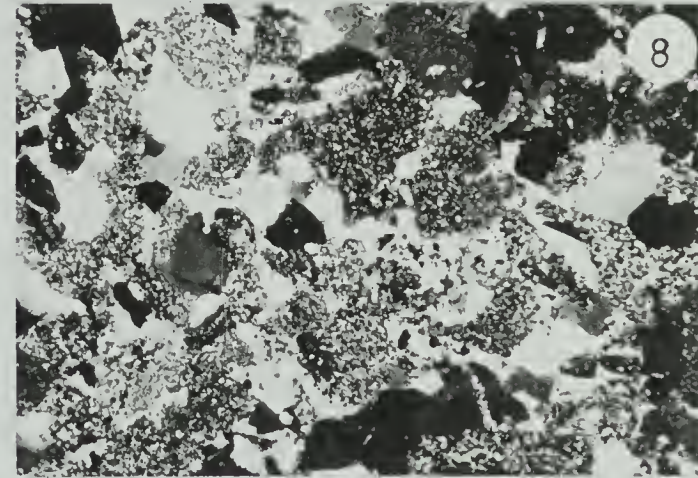
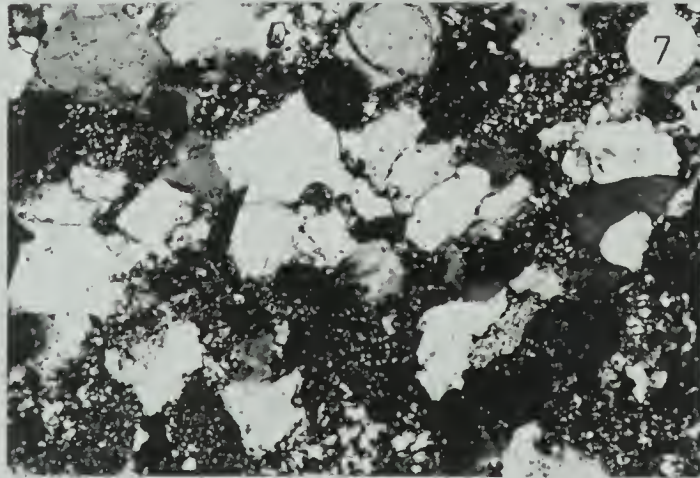
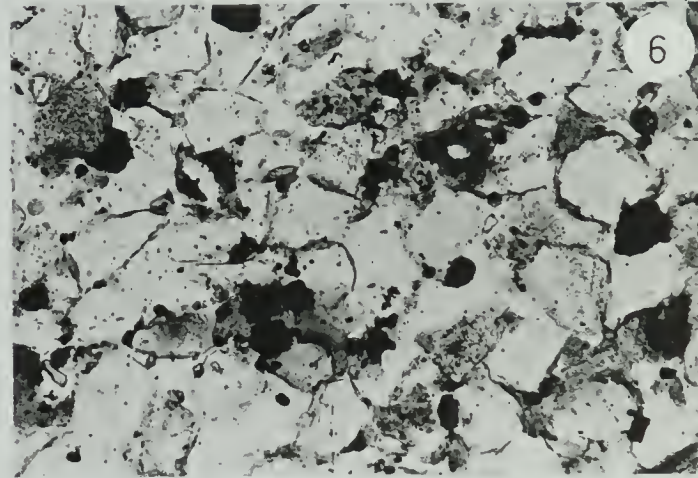
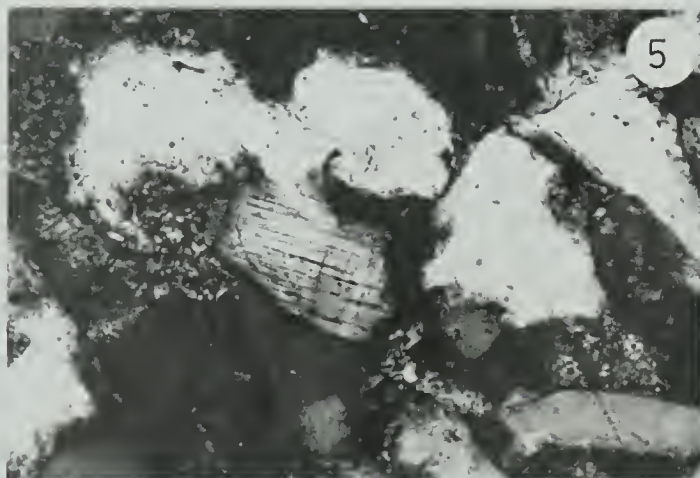
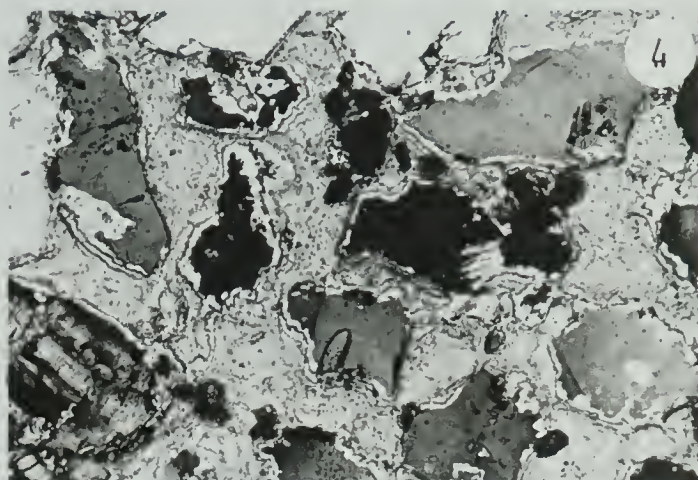
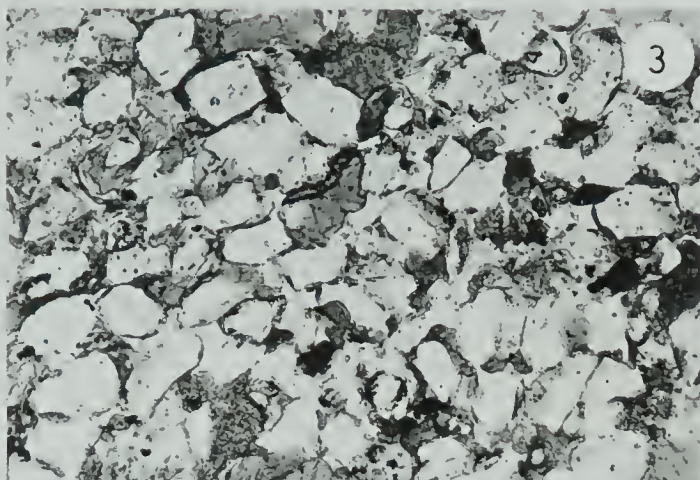
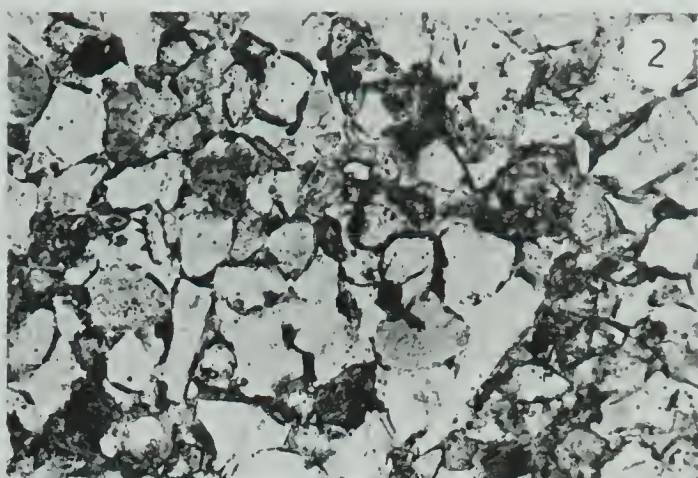
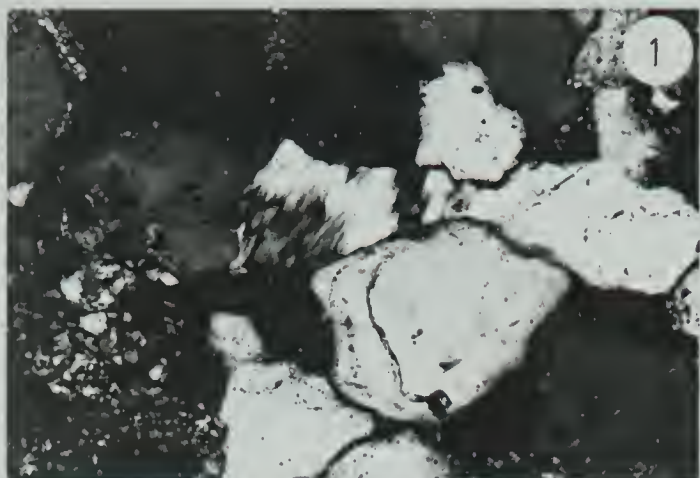


PLATE II

PLATE III

Thin Section Photomicrographs

1. Muscovite developing from chlorite. Note also dolomite rhomb replacement of chloritic matrix; both in central portion of photo. (F42, depth 335 feet), plane light, 102X.
2. Glauconite matrix (medium grey color). (F42, depth 285 feet), plane light, 40X.
3. Suturing developed in chert rich sandstone. (F52A, depth 841 feet), crossed nicols, 10X.
4. Abundant iron oxide rims surrounding glauconite, chamosite, and quartz grains. (F42, depth 312 feet), crossed nicols, 25X.
5. Foram test in siderite cement. (F42, depth 312 feet), crossed nicols, 25X.
6. Grain contacts primarily "tangential" or "long". (C2, depth 275 feet), crossed nicols, 32X.
7. Solid solution of clay lithoclasts (glauconite) with partial distortion of the glauconite pellets. (C2, depth 501 feet), crossed nicols, 32X.
8. Solid solution as above. (F42, depth 970 feet), crossed nicols, 25X.

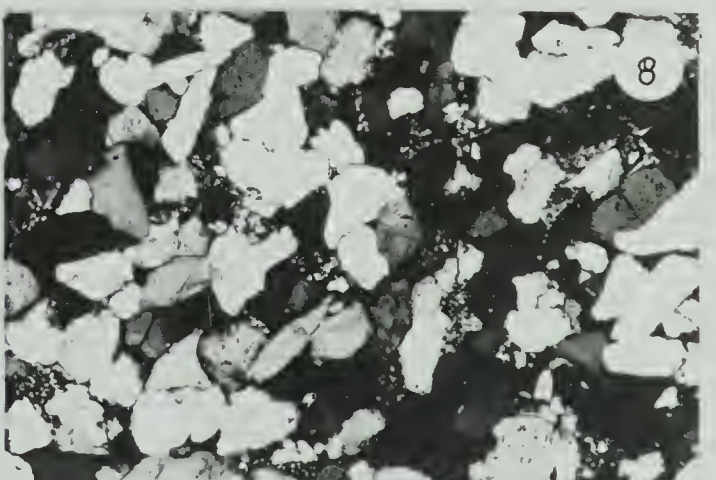
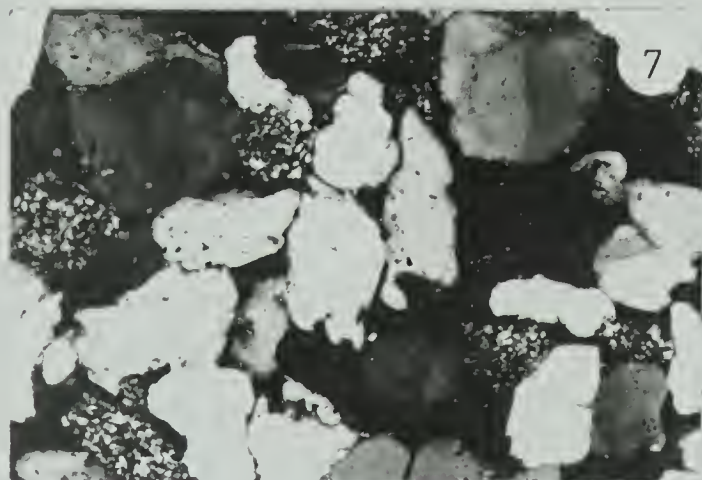
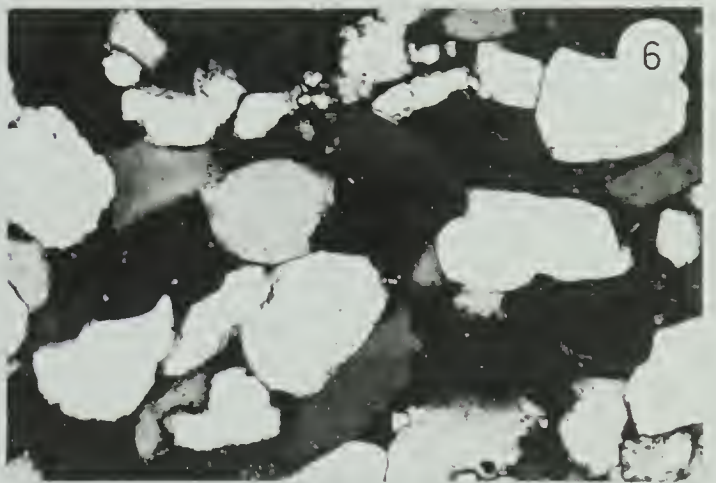
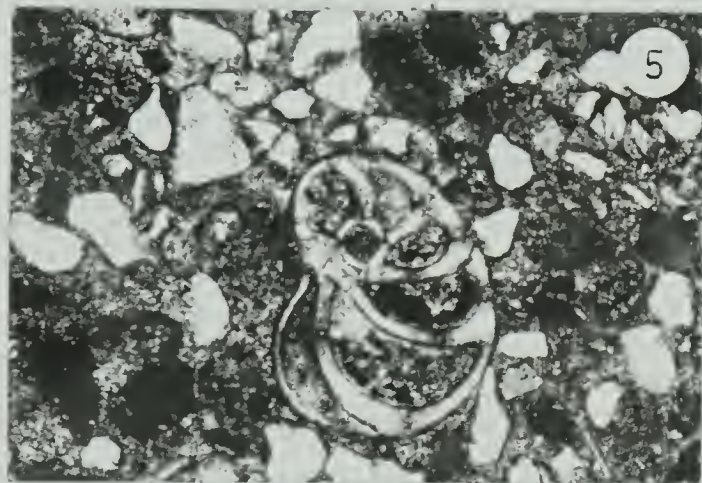
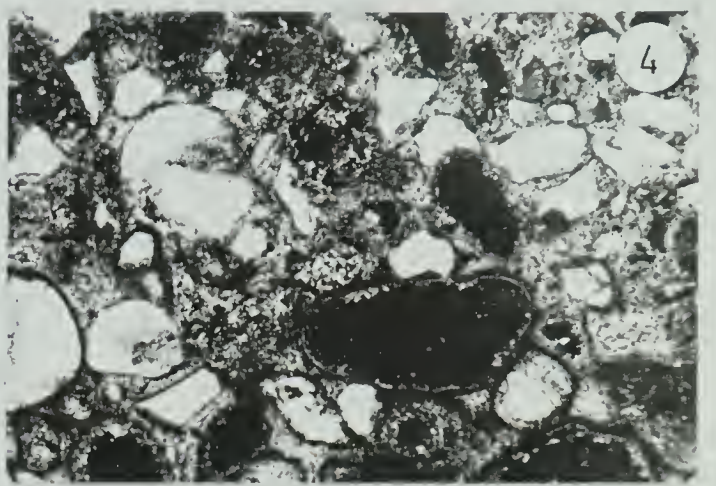
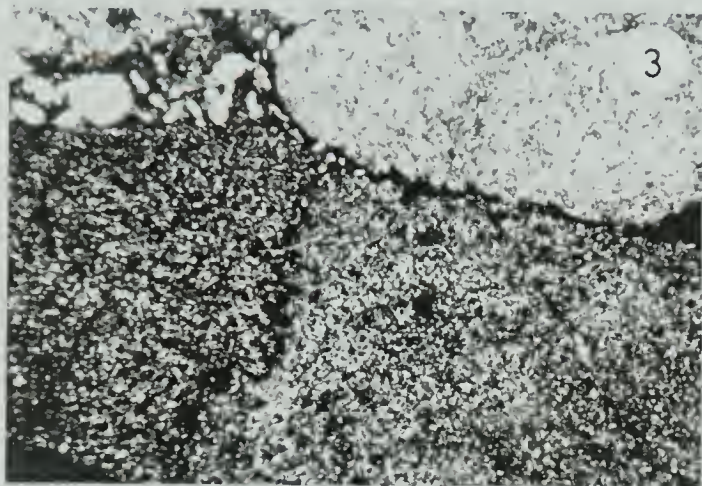
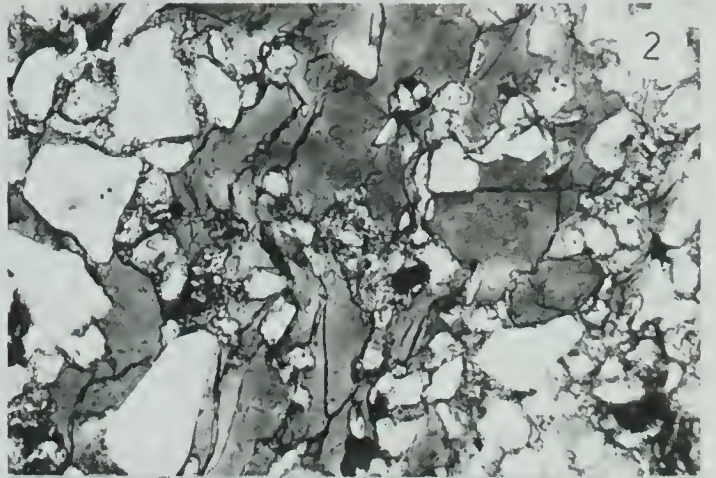
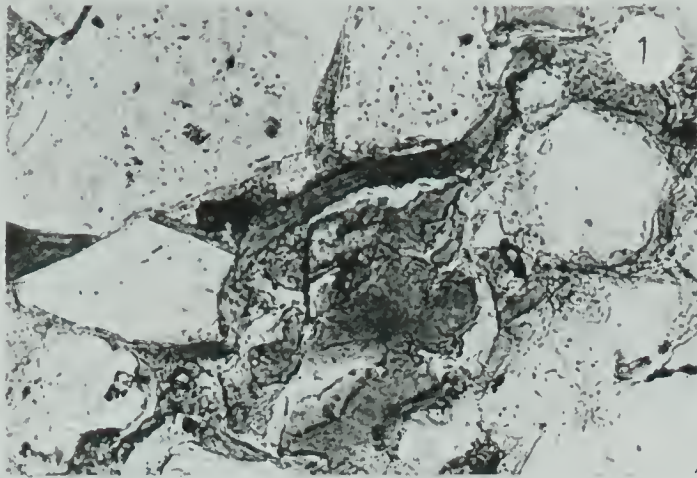


PLATE III

PLATE IV

Hand Specimen Photographs *

1. Typical bioturbated zone showing definite reworking by organisms. (F42, depth 250 feet)
2. Disturbed bedding with physical reworking and also some minor organic reworking. (F52A, depth 682 feet)
3. Convolute lamination(?), limited to interior of bed only, not affecting the upper and lower contacts. Sharp contacts may be micro-unconformities (diastems). (C2, depth 112 feet)
4. Coarse sandstone with strong organic reworking. (C2, depth 490 feet)

* all core is 1.5 inches in diameter

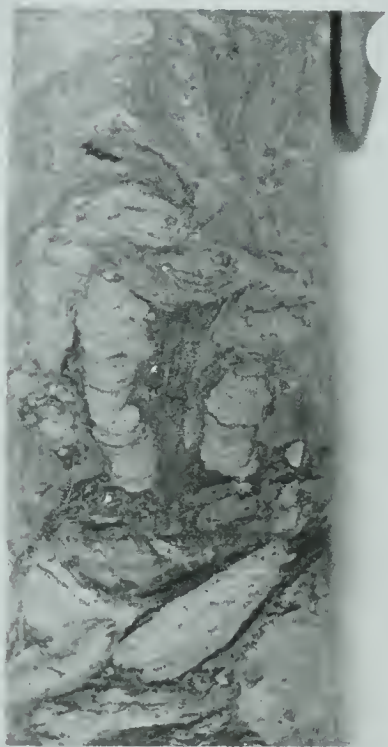
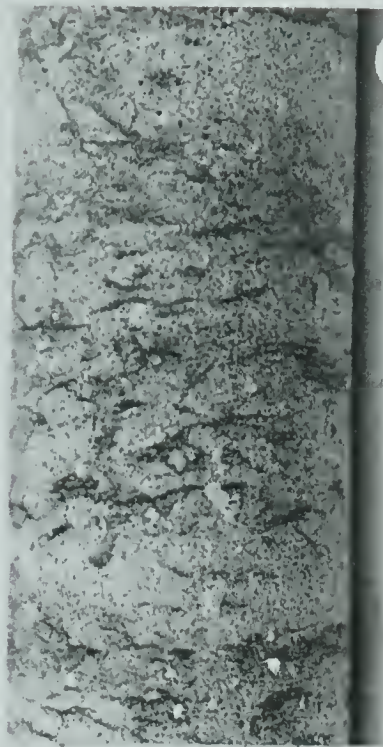
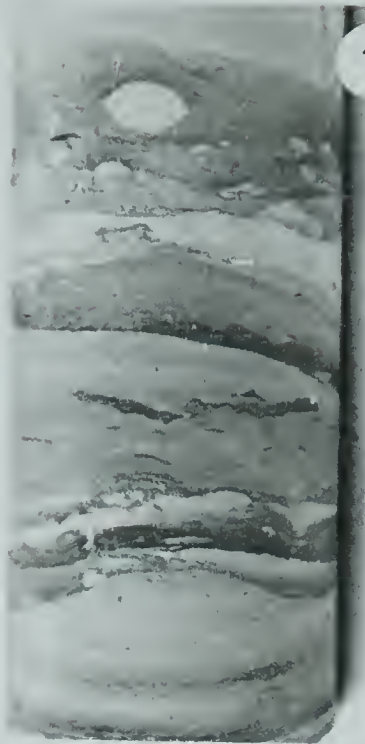


PLATE IV

DIAGENETIC FACIES

Introduction

The concept of diagenesis has received considerable attention over the years particularly with regard to its definition and limitations. The upper and lower limits of diagenesis have not been precisely defined. Diagenesis is gradational from weathering at one end to low grade metamorphism at the other end. According to Botvinkina (1959) diagenesis is a post-depositional feature, reflecting the phenomenon of "diagenetic stratification" which is not accidentally distributed but appears in those places where the conditions for its formation were prepared during the process of sedimentation. Teodorovich (1961) summarizes the concept of diagenesis in his statement, "At present most lithologists generally use the term diagenesis to indicate the combination of all processes (chemical, physical, physicochemical, biochemical, and geologic) that have controlled the conversion of sediments into consolidated rock without the accompaniment of orogenic forces".

Dapples (1967) states, "The progression of mineralogical change in sandstones from the time of accumulation to final lithification involves modification of the detritus during three interrelated, but fundamentally distinct stages in their history". These stages are identified as depositional (redoxomorphic), early burial (locomorphic), and late burial (phyllomorphic). He suggests that diagenetic facies can be recognized by the appearance of minerals sensitive to restricted physical and chemical conditions which represent the products of equilibria involving the interstitial fluids.

Physicochemical conditions

Authigenic minerals are of great interest since they may reflect in great measure the physicochemical conditions of sediment accumulation (Teodorovich, 1961). It is possible to designate physicochemical characteristics of the environment during formation and transformation of sedimentary rocks by using a series of minerals or individual mineral indicators. Krumbein and Garrels (1952) have constructed a graphic classification (Fig. 4) which is applicable to marine waters. These waters may have normal salinity, or they may be diluted to various degrees by fresh water, or concentrated somewhat by evaporation without significantly affecting the groups of end-members shown in the ten fields.

According to Krumbein and Garrels these ten fields can be grouped into three major environments: a) normal marine open circulation b) restricted humid (euxinic) and c) restricted arid (evaporite). This classification was originally designed to deal with primary sedimentary minerals. However, it is readily applied to the realm of secondary authigenic minerals as both primary and secondary minerals should be capable of reflecting environments of deposition. A problem does arise in the overlap of depositional environments and diagenetically modified environments. This means, for example, that organic matter may persist above the organic matter fence during times of rapid deposition and burial. The problem is not very serious as diagenesis generally does not completely mask the original depositional environment.

The graphic classification in question is divided by four "fences".

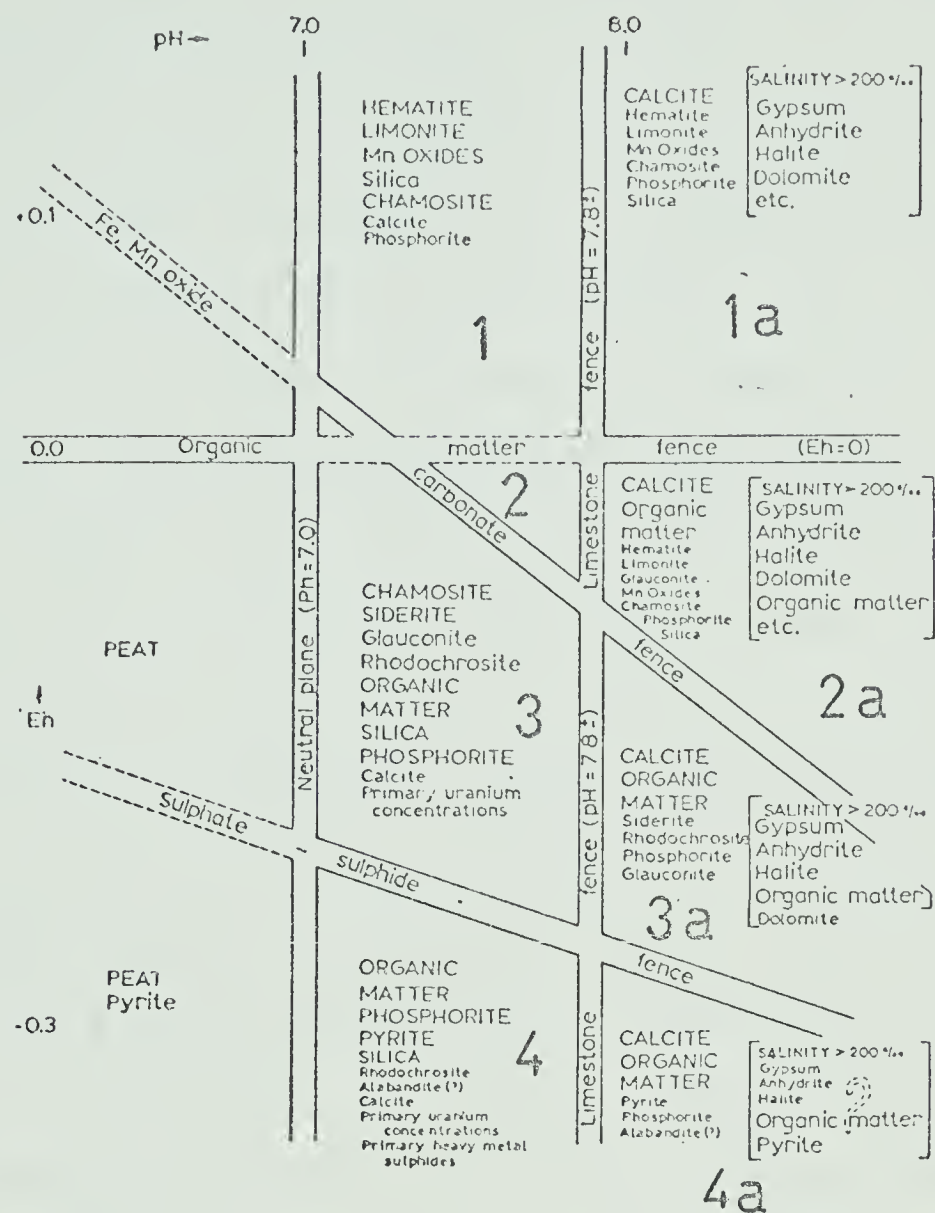


Figure 4: "Fence diagram" illustrating principal environments of sedimentation and diagenesis according to Eh and pH (after Krumbein and Garrels, 1952)

The Limestone Fence occurs at pH 7.8, and is independent of Eh as shown by its vertical position. To the right of this fence calcite is usually a predominant mineral while to the left of the fence its occurrence is minor and it has the role of an accessory mineral. The Organic Matter Fence, occurring at $Eh = 0$, separates oxidizing conditions which prevail above from the reducing conditions which prevail below. Organic matter, in general, is preserved most effectively under negative Eh conditions. The Fe-Mn Oxide-Carbonate Fence separates regions in which the conditions favor hematite and limonite formation from regions in which siderite is the dominant iron mineral formed. This fence slants, showing that the boundary is sensitive to both Eh and pH. The Sulfate-Sulfide Fence separates conditions under which abundant pyrite may form. It is also controlled by both Eh and pH conditions.

The upper portion of the diagram, that is, where Eh is greater than or equal to zero, represents normal marine open circulation conditions with pH ranging from neutral to mildly alkaline. A somewhat euxinic environment is represented between the Organic Matter Fence and the Sulfate-Sulfide Fence. The area below the Sulfate-Sulfide Fence, where organic matter and pyrite become increasingly important, represents a euxinic environment with substantial stagnation. (The eight fields of the fence diagram which will be applied to the Upper Sandstone Division sediments are numbered on Figure 4.)

With this basic classification in mind it was decided to examine the authigenic minerals occurring in the Upper Sandstone Division to see if they exhibited any trends as mineral indicators of geochemical facies

based on Eh and pH values.

Geochemical environments existing at Stony Creek

Nine compositional parameters were chosen to differentiate the various post-depositional geochemical environments. These are: glauconite, chamosite, organic matter (quantities based on thin section evaluation only), calcite, siderite, iron oxides, pyrite, chlorite, and quartz overgrowths. These are illustrated graphically in Figure 5 showing the distribution of authigenic minerals in the F52A, F42, and C2 wells. Based upon associations of authigenic minerals, six diagenetic zones and four diagenetic facies have been identified. The diagenetic zones are zones defined stratigraphically by authigenic mineral associations. Where the mineral characteristics of the zones are similar they have been grouped together to form diagenetic facies.

Going up section, the diagenetic zones have been labelled A through F. Zone A was identified only in the F42 and C2 wells. There is no predominant end-member associated with this zone. Calcite averages 3 per cent, organic matter 2 per cent, quartz overgrowths 2.5 per cent, glauconite 1.5 per cent and pyrite 1 per cent with a lack of authigenic siderite and chlorite. According to Figure 4, the diagenetic environment would fall into field 2 or 2a. The writer favors field 2 because the organic matter content is low and there is very little siderite. One would expect to find higher concentrations of pyrite and organic matter below the Sulfate-Sulfide Fence. Laterally, zone A changes very slightly from the F42 well to the C2 well. In F42 the average calcite content is double that in the C2 well. This would suggest a pH shift

toward 2a.

Zone B was also penetrated only in wells F42 and C2. This zone is characterized by an abundance of siderite (average 20.5 per cent) and organic matter (14 per cent) with pyrite, glauconite, and quartz overgrowths all less than 1 per cent. Zone B would fall into field 3 of the fence diagram. Laterally, zone B shows no significant variations.

Zone C occurs in all three wells. As in zone A, there is no predominant end-member associated with this zone. Calcite and chlorite average 1.5 per cent, pyrite and organic matter 2 per cent, glauconite 1 per cent and quartz overgrowths 3 per cent. Very minor changes occur laterally in zone C. This zone is assigned to field 2. The authigenic mineral assemblage and quantitative values are strikingly similar in zones A and C.

Zone D, which occurs in all three wells is characterized by two abundant end-members, organic matter and calcite. In addition, quartz overgrowths average 1 per cent, glauconite 1.5 per cent, and pyrite 2 per cent. From Figure 4, the diagenetic environment would fall into field 3a. It may be noted that the average organic matter content doubles in quantity in a west to east direction (F52A to F42), whereas the calcite content decreases by half.

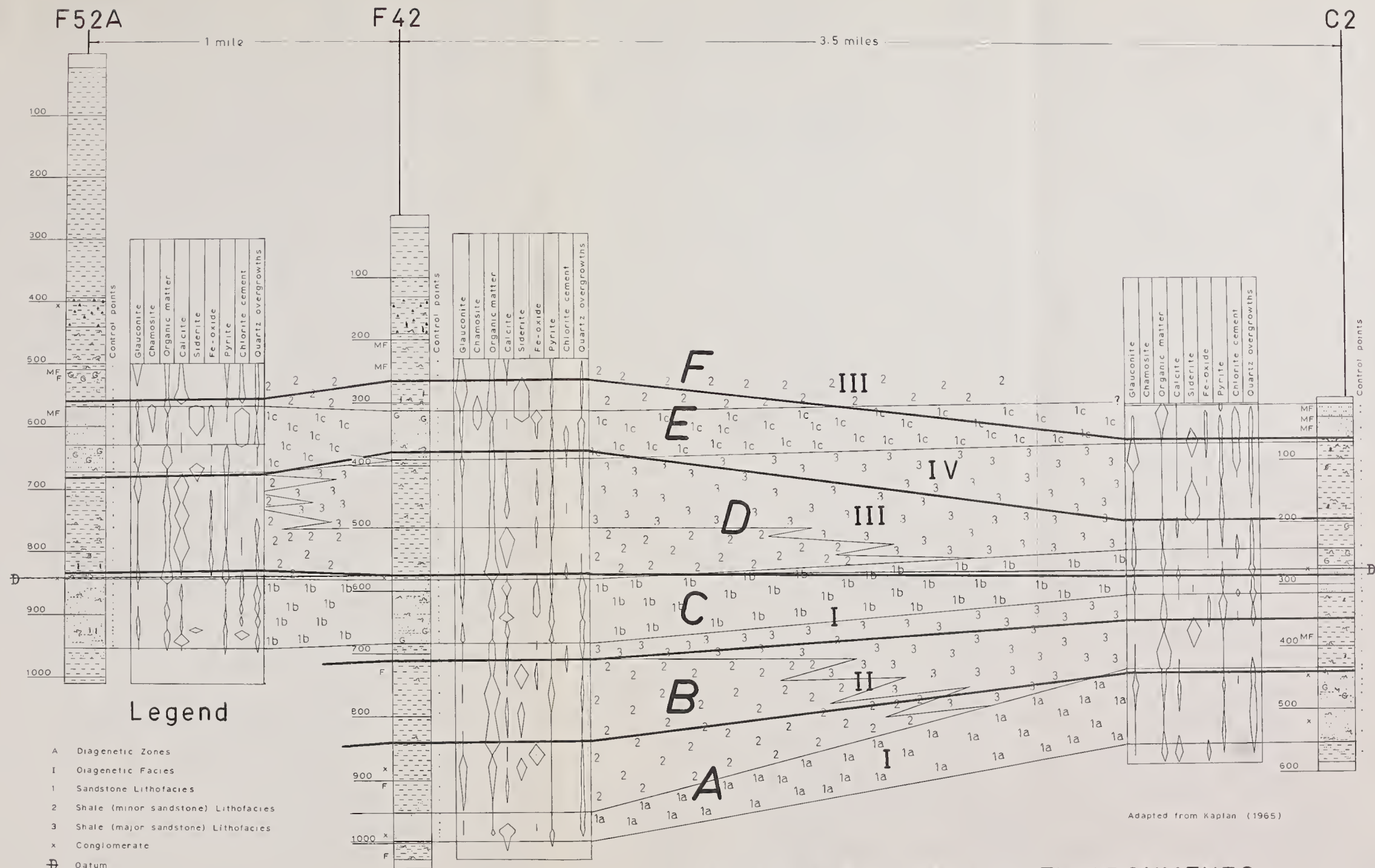
Zone E, the most distinct zone, occurs in all three wells. It is characterized by a siderite-chamosite-chlorite-iron oxide association, although the last named mineral is scarce in the C2 well. In addition, glauconite and organic matter have average values of 2.5 per cent, pyrite 2 per cent, and quartz overgrowths 1 per cent. The siderite, chlorite, chamosite, and iron oxides all show distinct decreases in

quantity toward the C2 well. The diagenetic environment of zone E would fall into field 3, progressing toward field 2 in the later history to account for the oxidizing conditions required for the formation of hematite.

Zone F has been identified in all three of the stratigraphic wells but is the least well defined of any of the zones, due to lack of core. Its most abundant abundant end-member is organic matter with a lesser amount of calcite. In addition, glauconite and quartz overgrowths have average values of 2 per cent, and pyrite and chlorite 1.5 per cent. Zone F would fall into fields 3a or 4a in Figure 4. Laterally, zone F shows considerable change from the F52A to the C2 well. Organic matter substantially increases in this direction while the calcite content substantially decreases. Zone F has a resemblance to zone D. Both show the substantial calcite and organic matter content changes just described.

In all of the zones, the organic matter content is "high" (greater than 2 per cent, Pettijohn, 1957) in relation to the quantities of the authigenic minerals. Zone A has a low organic matter content (average value of 2 per cent) while zone B has a high content (average value of 14 per cent). This rhythmic low-high organic matter content continues in strict fashion through each of the other zones. Other similarities, other than the organic matter content, between zones A and C and between zones D and F serve to consolidate the six zones into four diagenetic "facies". Facies I (zones A and C) is characterized by the lack of a predominant mineral and is assigned to field 2. Facies II (zone B) is characterized by an abundance of both organic matter and siderite content and is assigned to field 3. Facies III (zone D and F)

is assigned to field 3a and contains about equal amounts of organic matter and calcite. Facies IV (zone E) is defined by the mineral assemblage siderite-chamosite-chlorite-iron oxide and falls into fields 2 and 3.



DIAGENETIC FACIES ENVIRONMENTS
STONY CREEK, NORTHWEST TERRITORIES
FIGURE 5



Environmental reconstruction

Lithofacies:

In the Upper Sandstone Division five basic lithologies have been observed: a) conglomerates, b) sandstones, c) siltstones to very fine grained argillaceous sandstones, d) shale with major sandstone intercalations, e) shale with very minor sandstone intercalations. These have been grouped into three basic lithofacies: 1) sandstone lithofacies, 2) shale (minor sandstone) lithofacies, 3) shale (major sandstone) lithofacies which are numbered 1, 2, and 3 respectively, in Figure 5.

Because the conglomerates occur in more than one lithofacies and because they are used in determining the datum they will be dealt with separately. The conglomerates of the Upper Sandstone Division are mostly paraconglomerates lying within rather than at the base of a lithofacies unit. The phenoclasts consist of chert pebbles or sandstone lithoclasts (which resemble sandstones of the Upper Sandstone Division) in an argillaceous matrix. The conglomerates are poorly sorted with both rounded and angular phenoclasts and vary in thickness from six inches to two and one half feet. These conglomerates are particularly abundant in Lithofacies 1a of the C2 well. In two other occurrences, one in the F52A well (Lithofacies 1b), and the other in the F42 well (Lithofacies 1b), conglomerates lie at the top of a sandstone unit. The stratigraphic datum for Figure 5 is based upon a lithologic correlation between the latter two occurrences and one of the conglomerates in the C2 well (Lithofacies 1c). The conglomerate in these three

occurrences has nearly identical percentage compositions of chert, quartz, and matrix. It may be interpreted as a product of submarine slumping initiated by basin-edge subsidence or as an erosional hiatus. The datum conglomerate in the F52A well and F42 well is associated with shale units. In the C2 well the conglomerates are all within sandstone units. In contrast, the two more westerly wells suggest substantially more subsidence reflected by the association of conglomerate with overlying shale units. These relationships may imply basin-edge subsidence to the west.

Lithofacies 1: The sandstone of Lithofacies 1a in well F42 is light grey (N7) to very light grey (N8) in color with occasional thin shale laminations which are very abundant in the lower ten feet of the unit. Where the sandstones are relatively clean with only thin shale laminations the glauconite content is negligible. The grain size, in the F42 well, varies from upper fine at the base to lower fine at the top of the unit (* in all cases, "upper" refers to the coarse fraction of a certain grain size limit and "lower" to the fine fraction). Eastward (Lithofacies 1a, C2 well), the sandstone changes color slightly from medium light grey (N6) to light olive grey (5Y 6/1). The color change is generally associated with an introduction of minor glauconite. The thin shale laminations of the F42 well increase in thickness and quantity in the C2 well. Much of the sandstone here is argillaceous and physically reworked in contrast to the same sandstone in the F42 well. The grain size fluctuates from upper fine to lower medium; a definite increase, upward, in grain size over the same sandstone in the F42 well.

In addition, the grain size generally becomes coarser in the east direction (F42 to C2). Contacts of Lithofacies 1a with the overlying and underlying shale units are gradational.

Clean sandstone (5Y 6/1) with thin shale laminations occurs again in Lithofacies 1b of the F52A well but with the addition of 3 to 5 foot units of intercalated shale and sandstone beds in which physical and organic reworking occur. The grain size here fluctuates from lower to upper fine. In the F42 well the shale occurs as occasional stringers of argillaceous material up to 1/32 inch thick in contrast to the more continuous thin shale laminations of the F52A well. The intercalated zones show organic reworking as in the F52A well (3 to 5 foot units) but these have here increased in thickness (600-620* feet and 640-660 feet). The grain size remains constant at the lower fine limit. The Lithofacies 1b sandstone in the C2 well varies from clean quartz to glauconitic. The basal portion of the facies is clean sandstone (N7) with occasional shale laminations, followed by an argillaceous conglomerate (275-276½ feet). The upper 10 feet is glauconitic with abundant shale lenses. The grain size here fluctuates from the lower fine to the upper very fine limit. Laterally, Lithofacies 1b shows no change in grain size.

Lithofacies 1c varies slightly from Lithofacies 1a or 1b. The basal portion of this facies consists of glauconitic siltstone with up to 30 per cent shale interbeds showing some physical reworking. The siltstone changes abruptly upward into a clean sandstone with minor glauconite and a single 5 foot shale bed with minor glauconite (612-617 feet). Grain size, for the sandstone, varies from upper fine sand

* depth interval

at the base to lower fine at the top. Eastward (F42), the upper part of Lithofacies 1c (310-360 feet) is glauconitic and the lower part (360-390 feet) contains interbedded sequences of shale (up to two inches thick) and sandstone with physical reworking. The grain size changes sharply from upper very fine at the base to lower medium at the top. In the C2 well, Lithofacies 1c is characterized by a friable sandstone (10Y 6/2) with numerous pockets of pelecypod shell debris, and a single shale interbed (55-60 feet) with minor physical reworking. In this well, the grain size is constant at the lower fine limit.

All Lithofacies 1 contacts (1a, 1b, and 1c) are gradational with the overlying and underlying shales (Lithofacies 2 and 3) except in two occurrences where Lithofacies 1b of F52A and F42 ends abruptly in argillaceous conglomerates.

Lithofacies 2-3: The shales of the Upper Sandstone Division sediments vary from shales with major sandstone intercalations (30-50 per cent; Lithofacies 3) to shales with minor sandstone intercalations (up to 5 per cent; Lithofacies 2) within the same lithologic unit. Except for the degree of sandstone intercalation, these shales are essentially constant in color (N4) and composition (illitic with minor chlorite and kaolinite throughout the stratigraphic interval studied. In all cases, Lithofacies 2 becomes Lithofacies 3 in an eastward direction. In Lithofacies 3, the sandstone intercalations are cross-bedded when of substantial thickness (2 to 3 inches thick). The uppermost occurrence of Lithofacies 2 occurs only in the two westerly wells. In the F52A and F42 wells the shale is interbedded with glauconitic sandstone (8 inches to 4.5 feet thick) and contains only

minor intercalations of sand with pronounced pelecypod fossil zones. The glauconitic sands in both wells vary from thinly laminated to cross-bedded. Some of the typical bedding characteristics of the three Lithofacies are shown in Plate IV, 1-4.

Exum and Harms (1968) studying the Cretaceous of Western Nebraska, recognized three facies which they called the central-bar facies, the bar-margin facies, and the inter-bar facies. The central-bar facies is characterized by sandstone with few shale partings, abundant low angle cross-stratification, no vertical variation in grain size and a low matrix content. It is similar in appearance to the clean, or slightly glauconitic reworked sands of Lithofacies 1a, 1b and 1c at Stony Creek.

Their bar-margin facies consists of a "mottled intermixture" of sandstone and shale with abundant burrows and "augen" burrows. The texture of these sandstone lenses (augen burrows) is identical to that in the central-bar facies and they show cross-stratification where physical or organic reworking is absent. Exum and Harms' "mottled intermixture" is similar in appearance to Lithofacies 3 (shale with major sandstone intercalations) of the Stony Creek sediments, which show physical or organic reworking in part. Their "augen" burrows have been called organic reworking by this writer, but judging from their photographs the characteristics are very similar if not identical.

The third facies, the inter-bar facies, is composed primarily of shale with scattered thin layers of quartzose sandstone whose texture is also identical to that of the central-bar facies. A similar shale with minor sandstone intercalations (Lithofacies 2) is also

present at Stony Creek where the sandstone interbeds often decrease to thicknesses of 1/16 of an inch. Petrographic analysis shows that these sands differ only slightly from the thicker sand units except for their higher organic content. That is, the interbedded sands, both in major and minor sandstone intercalations are essentially identical to the cleaner, thicker sand units.

The environment of the Upper Sandstone Division is probably analogous in many respects to those Cretaceous deposits of Nebraska studied by Exum and Harms. These Upper Sandstone sediments were deposited in a broad shallow sea that extended generally northwest to southeast. During mid-Lower Cretaceous time numerous fluctuations occurred in the position of the strandline, sometimes encroaching southeastward over the gentle slope of the adjoining land mass and at other times retreating northwestward toward the deeper portions of the basin. Pike, (1947; in Hollenshead and Pritchard, 1961) has pointed out that at any given time one of at least three conditions is possible: 1) the rate of sedimentation predominated over subsidence, causing regression of the shoreline; 2) the rate of subsidence predominated over sedimentation, resulting in transgression of the shoreline; 3) the rates of sedimentation and subsidence were in equilibrium, causing the shoreline to remain stable, resulting in deposition of a relatively thick sand section. This equilibrium is responsible for the development of sand build-ups such as broad bars, shoals, stillstand sands (Krumbein and Sloss, 1963) or sandstone benches (Hollenshead and Pritchard, 1961). This equilibrium was present for considerable periods of time at Stony Creek. There is no indication that these sand build-ups were emergent

and little evidence that they effectively separated a lagoon from the Cretaceous sea.

The faunal content consists of undiagnostic thin walled pelecypods and Foraminifera. According to Mountjoy et al (1969), open marine conditions are represented by most calcareous forams, and restricted marine conditions by the abundance of agglutinated forms. The forams of the Upper Sandstone Division consist of both calcareous and agglutinated forms (Channey, personal communication) with the latter greatly predominating. This would imply at least partially restricted marine conditions. Phleger (1960), mentions that sand lagoon barriers may have a mixture of nearshore, open-ocean and lagoon benthonic Foraminifera. This would account for the slight mixing of calcareous and agglutinated forms. Lithofacies 2 appears to coincide with the "lagoonal deposits", becoming more turbid (Lithofacies 3) as one approaches the shoal.

Sands of succeeding shoals might be expected to possess at least minor differences in mineralogical and physical characteristics. Several kinds of evidence indicate lateral interfingering of lithologies and also aid in defining the seaward and landward sides of the shoals:

- 1) the degree of organic and physical reworking in the sand units increases to a maximum adjacent to the shoal axis;
- 2) the number and thickness of sandstone intercalations increases in an eastward direction;
- 3) the highest porosities occur on the westward side of the shoal axis;
- 4) the glauconite content generally increases in the eastward direction;
- 5) the westward side of the shoal consists of clean sand with thin shale laminations which are relatively undisturbed.

The diagenetic zones are defined by authigenic minerals which are early in the diagenetic history and hence reflect depositional environment. They should, therefore, be capable of indicating depositional time planes.

Diagenetic facies:

The diagenetic zones may be considered as six stages in the history of the paleoenvironment. In the first stage (diagenetic zone A) the sandstone shoal facies is best developed in the C2 well with the sand interfingering landward with the shale-minor sandstone facies (Lithofacies 2). The sandstone shoal facies is argillaceous, slightly glauconitic, and shows abundant physical reworking. Westward (F42) the sand is very clean with minor thin shale laminations, which are relatively undisturbed, and only trace amounts of glauconite.

Stage 2 (diagenetic zone B) marks progressive deepening of the mid-Lower Cretaceous sea. The shale-minor sandstone facies (Lithofacies 2) in the F42 well gives way eastward to the shale-major sandstone facies (Lithofacies 3). Principal development of the sandstone shoal facies at this time is to the west of the F52A well.

A regressive fluctuation is defined by stage 3 (diagenetic zone C) with the development of the sandstone shoal in the two westerly wells (F52A and F42). The sandstone here is clean with minor shale laminations, slightly glauconitic and with minor reworking which increases slightly in intensity in the eastward direction. Eastward of the shoal axis (in the C2 well) the sandstone facies is characterized by minor to abundant shale laminations with an absence of physical reworking, a slight decrease in grain size, and considerable glauconite. Going from west to east the sandstone facies interfingers with the shale-

major intercalated sandstone facies (Lithofacies 3). A conglomerate, lying on top of Lithofacies 1b in the F52A and F42 wells, and within Lithofacies 1b in the C2 well, reflects the late stages of sea withdrawal. The conglomerate is erosional in part, and forms a very minor hiatus (?) of unknown duration.

Diagenetic zone D (stage 4) represents an episode of rapid transgression with subsidence along the basin-edge. This is reflected in the thicker shale-minor intercalated sandstone facies (Lithofacies 2) which gives way eastward to the shale-major intercalated sandstone facies (Lithofacies 3). Development of the sandstone shoal facies must be west of the F52A well.

In stage 5, diagenetic zone E, another regressive period is documented with the development of the sandstone shoal facies in the F52A and F42 wells, interfingering seaward into the intercalated shale-major sandstone and shale-minor sandstone facies. The shoal is characterized by an argillaceous, glauconitic sandstone in F52A which continues into F42 but with the addition of minor reworking.

Another transgressive pulse (stage 6) occurs in diagenetic zone F with formation of the landward portion of the sandstone shoal facies in the C2 well. Principal development of the shoal facies is to the east of the C2 well.

As mentioned previously, migration of the sand shoal (Lithofacies 1) seaward or landward is related to fluctuations of the strand line. Three regressive-transgressive cycles are present: A-B, C-D, and E-F. These cycles or stages are illustrated diagrammatically in Figure 6. They are interpreted as asymmetric cycles caused by rapid subsidence

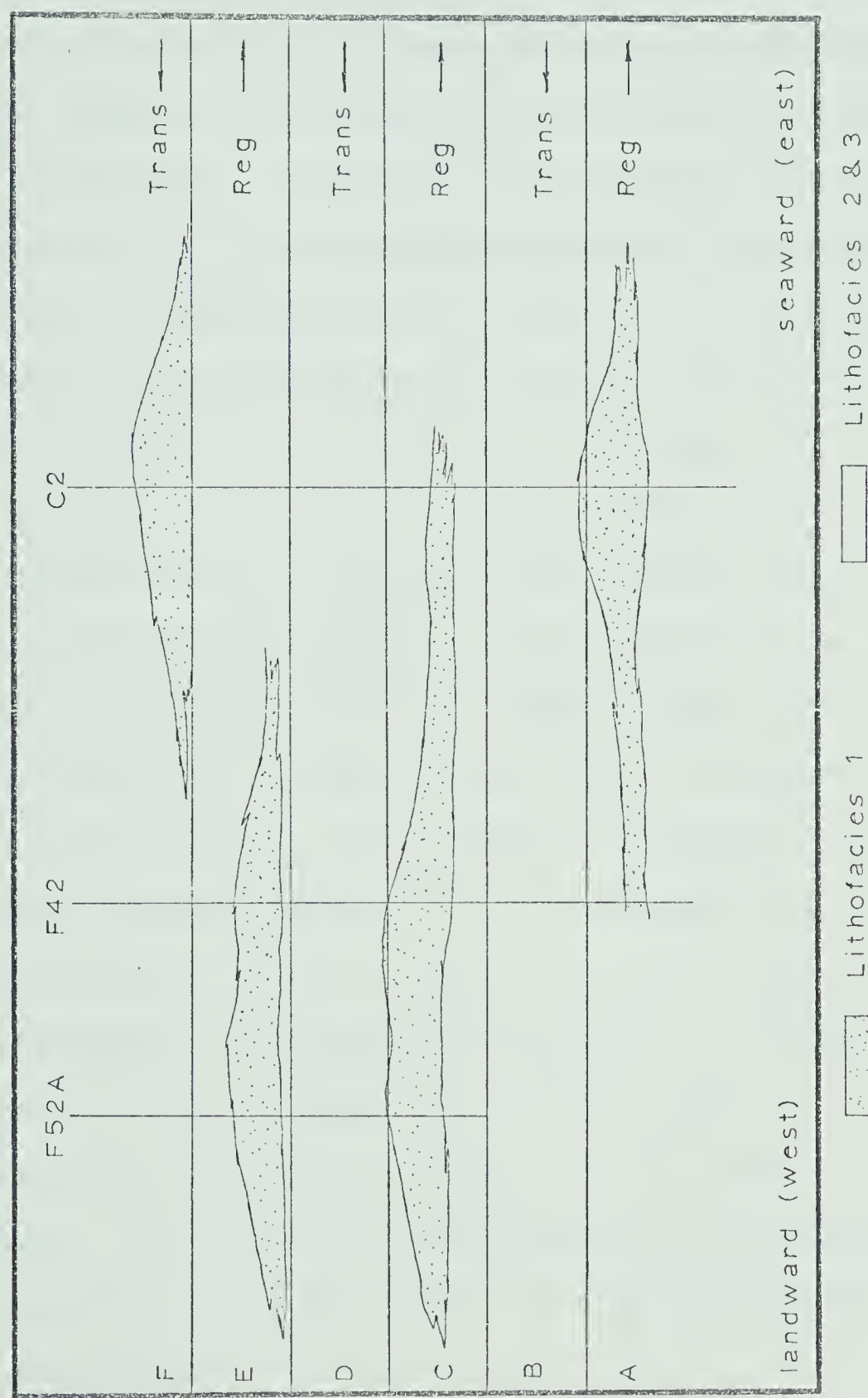


Figure 6: Diagrammatic sketch illustrating sandstone shoal development during mid-Lower Cretaceous time

pulses producing rapid transgression followed by a slower regression. The diagenetic zones, based on authigenic minerals, provide chemical clues to depositional surface correlations for detailed environmental reconstruction, particularly where the application of fossils is limited because of long ranging forms, as is the case for the Upper Sandstone Division. Integration of the diagenetic zones and lithologic units enables a more accurate interpretation of the depositional site to be made. From an examination of Figure 5, it is seen that the diagenetic zones consistently transect the lithologic boundaries. Rather than simple sand to sand unit correlations, this overlap of boundaries implies merging of lithologies through lateral interfingering.

Interpretation of a landward versus a seaward direction from the evidence available is arguable, but the writer favors an interpretation of the landward side to the west. Notable changes from west to east in the three wells examined, and upon which the interpretation is based are as follows: 1) the number of conglomerates and number of sandstone intercalations increases in the eastward direction; 2) the westward side of the shoal consists of fairly clean sand with thin shale laminations which are relatively undisturbed; 3) the glauconite content generally increases in the eastward direction; 4) the amount of organic matter increases eastward; 5) the carbonate cement increases westward; 6) the forams are agglutinated forms, implying partially restricted marine conditions, and lie on the westward side of the shoals (Figure 5)

Interpretation of bars and particularly their landward and seaward edges is of great interest to the petroleum industry. According to

Curtis et al (1961) bars make up 23 per cent of all stratigraphic traps studied by them. The identification of diagenetic zones serves as a useful tool in identifying sand bar or shoal development and aids in distinguishing the fore-bar from the back-bar. One disadvantage of this particular study was the restriction in lateral control by the close spacing of the wells. Because of this, one was unable to map a full fore-bar, main bar, and back-bar sequence in any one stage of development. Nevertheless, the study could serve as a pilot model for more regional problems of this nature.

SUMMARY AND CONCLUSIONS

The findings of this study may be summarized in the following points:

- (1.) Three progressive stages of diagenesis (as defined by Dapples, 1967) occur within the Upper Sandstone Division sediments. Redoxomorphic (oxidation-reduction) reactions involving iron characterize the very early stages of burial. Locomorphic changes (cementation and mineral replacement) define the lithification stage. The phyllomorphic stage (authigenesis of micas and feldspars) characterizes the late burial stage. The shelf-like sands of the Upper Sandstone Division do not progress very far into the phyllomorphic stage of diagenesis as tectonic events are distinctly lacking for these mid-Lower Cretaceous sandstones.
- (2.) It has been established by petrography that glauconite and chamosite were the first authigenic minerals to form during diagenesis. Both are penecontemporaneous in origin. This was followed by the formation of chlorite cement and authigenetic quartz overgrowths, sometimes in reverse order. This stage was in turn followed by the precipitation of carbonate cements, both calcite and siderite. The last authigenic minerals to form were feldspar, muscovite, and pyrite.
- (3.) Mineral assemblages, identified by the pH and Eh of the interstitial fluids, occur as a result of chemical reactions taking place during diagenesis. A study of these authigenetic minerals reveals six diagenetic zones and four diagenetic facies reflecting to a major extent environmental conditions existing at the time of mid-Lower Cretaceous sedimentation. Diagenetic zone A has no predominant end-

member associated with it. Zone B is characterized by an abundance of siderite and organic matter. Diagenetic zone C is similar to zone A in that it lacks a predominant end-member. The two abundant end-members, organic matter and calcite identify diagenetic zone D. Zone E, the most distinct diagenetic zone, contains the mineral association siderite-chamosite-chlorite-iron oxides. Diagenetic zone F contains organic matter as its most abundant end-member with a lesser amount of calcite. Similarities between zones A and C and zones D and F serve to consolidate the six zones in four diagenetic facies.

(4.) The Upper Sandstone Division sediments were deposited in a fluctuating regressive-transgressive system marked by periods of rapid transgression, then periods of stability and followed by periods of slower regression. Consideration of the relationship between diagenetic facies and lithofacies has produced an interpretation of depositional surfaces suggesting a shifting series of broad bars or sand shoals.

(5.) Preservation of porosity is related to the proportion of clay rock fragments to chemical cement to quartz framework grains.

Intuitively, porosity is highest where little or no clay matrix is present. The framework grains resist pressure (no pressure solution is evident) producing a mixture of both squeezed and unsqueezed clay rock fragments. It appears that the clay rock fragments generally inhibit the precipitation of chemical cements because the latter is usually low when the clay rock fragment content is high. This means that diagenetically controlled porosity can be predicted by knowledge of the clay components of a given sandstone suite. The principal factors causing porosity reduction are simple pore filling and poor

sorting. In addition, three generalities have been observed. First, the chert-rich sandstones in this study are associated with high porosities because of the lack of overgrowth development. For this reason chert-rich sandstones serve as potential petroleum reservoirs but only at shallower depths. With greater depths, chert-rich sandstones readily undergo pressure solution. Second, the best reservoir rock would be an essentially clay matrix-free quartzose sandstone with either clay coatings or thin chlorite rims on the quartz grains. The clay and chlorite seem to inhibit the precipitation of chemical cements. The occurrence of squeezed and unsqueezed clay pellets appears to have much the same effect as clay or chlorite coated quartz grains in preserving porosity. Third, porosities appear to be higher on the landward side of the shoal but the porosities may increase seaward as the chert content increases.

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APPENDIX A

F52A	total depth 1003'	ground elevation 1000'
23-395'	Shale, N5 (medium-grey), uniform color, trace silt, very consistent up to 160', at 160-240' quite friable, trace coal and glauconite, at 300' pyrite, trace chert pebbles at 395'	
395-440'	Shale with chert pebbles, at 395-402' get minor scattered chert pebbles, at 402-405' a conglomerate with abundant chert pebbles up to 1" in size and approximately 25% of rock, trace of carbonate cement	
440-508'	Shale with minor sandstone interbeds, at 440-450' shale interbedded with sand lenses up to 1" thick which are pyritic but very clean, at 460-470' sand lenses now occur as lenticules with sedimentary boudinage structure, sand shows some cross-bedding, abundant copper stain, very tight, porosity less than 4 per cent, at 470-480' back to sand beds up to 8" thick, 490-500' shale-sand intercalated approximately 50:50	
508-567'	Shale with minor lithic glauconitic sandstone interbeds, 500-510' shale with up to 15% lithic glauconite sandstone, very fine grained but clean (quartz 90%, glauconite 10%), minor reworking with presence of sand filled burrows, 510-517' shale-sand intercalations, 517-520' a very argillaceous siltstone or silty shale with abundant glauconite 5GY 2/1 (greenish-black), 520-522' a good pelecypod fossil zone, 520-530' back to shale with lithic sandstone interbeds up to 8" thick, 528-530' shows shale or siltstone with heavy glauconite as at 517-520', 530-540' get 6" shale, 12" glauconite sandstone, 4' shale with minor sand beds, 4½' laminated glauconitic sandstone, 540-550' get 1½' glauconitic sandstone, the remainder is shale with interbeds of sand, 550-567' shale with lithic glauconitic laminated sandstone	
567-627'	Sandstone, 5Y 6/1 (light olive-grey), 567-570' fairly argillaceous but moderate sorting, porosity up to 8%, 570-612' trace glauconite, porosity less than 5%, 612-617' predominantly shale with minor sandstone, 617-625' sandstone as at 570-580'; 567' fine, 580' lower fine, fossil pelecypods at 584', 590' lower fine, 600-610' lower fine, 620' very fine, 627' upper fine.	

- 627-670' Siltstone, 5Y 6/1 (light olive-grey), 627-640' siltstone with shale interbeds up to 30%, 640-650' siltstone approaches a very fine grained sandstone in places, 650-670' intercalated siltstone-shale, some reworking
- 670-841' Shale, N4 (medium dark grey), 670-765' shale with intercalated very fine sandstone, reworking in part, soft sediment boudinage, 765-810' sandstone lenses minor to very minor and show some cross-bedding, 800-810' get trace carbonate cement, 810-820' get intercalated sandstone-shale with burrows and soft sediment boudinage, 820-840' get shale with sand lenses minor to very minor, 840-841' an argillaceous conglomerate with chert and sandstone phenoclasts up to 3/4" in size
- 841-950' Sandstone, 5Y 6/1 (light olive-grey), 841-850' very well sorted, very clean, porosity up to 15%, slight trace carbonate cement up to 851', very thin shale laminations, 860-877' get shale intercalated with very fine sand with soft sediment boudinage, 877' back into very clean sandstone with porosity approximately 12%, 900-910' slight color change 5Y 6/1 to 5GY 6/1 (light olive-grey to greenish-grey), 910-920' very thin shale laminations, 920-925' sandstone intercalated with shale, 925-930' sandstone with sand filled burrows, 930-940' sandstone very clean, trace argillaceous material (rock fragments), 940-950' sandstone with occasional 8" zones of intercalated sandstone-shale; 845-860' lower fine, 869' upper fine, 880-910' lower fine, 920' upper fine, 925' lower medium with some coarse clasts, 930' upper fine, 940-950' lower fine
- 950-1000' Shale with very fine sandstone interbeds, 950-960' shale 60% sand 40%, 960-970' shale 80%, sand 20%, 970-980' sand becoming less pronounced, shows cross-bedding in part, 980-990' shale with minor sandstone interbeds, 990-1000' sandstone beds becoming very very minor
- 1000-1003' Shale, N4 (medium dark grey), very slightly silty, soft, fissile

- F42 total depth 1020' ground elevation 1075'
- 20-129' Shale, N4 (medium dark grey), with sandstone lenticules and laminations, very friable, 60-70' minor sandstone lents show some glauconite, 70-100' a very dirty siltstone or a very silty shale, becoming almost an argillaceous siltstone from 100-129' with traces of pyrite
- 129-190' Shale with chert pebbles, 129' get an 8" zone of chert pebbles which are up to $\frac{1}{2}$ " in size and well rounded, chert pebbles occur sporadically up to 190', 180-190' very silty shale or argillaceous siltstone with some soft sediment boudinage, 183-185' get glauconite filled burrows with associated pyrite, 188-190' more glauconite beds with minor chert pebbles and pyrite
- 190-310' Shale with minor intercalated sandstone, 190-200' argillaceous siltstone-shale with minor reworking and soft sediment boudinage, 200-210' N5 shale with sandstone-siltstone lents, trace malachite and occasional pelecypod shells 209-210', 210-230' get minor reworking, sand lenses up to 3" thick, abundant soft sediment boudinage, cross-bedded in part, 230-240' abundant pelecypod shells and cross-bedded sandstones up to 1" thick, 240-300' cross-bedded and thinly laminated sandstones, porosity less than 6%, 300-310' argillaceous siltstone with inclined or horizontal bedding, occasional pelecypod shells, becoming 5Y 8/1 (yellowish-grey)
- 310-390' Sandstone, 5Y 8/1, porosity 6-10%, abundant glauconite, 310-330' high glauconite content, fairly argillaceous, bedding thin and sub-horizontal, carbonate cement in part, 330-340' color change to 5Y 6/1 (light olive-grey), porosity 3-8%, very thinly laminated, trace glauconite, 340-350' fairly tight with abundant iron staining, carbonate cement in part, 350-360' quartzose sandstone interbedded with N3 shale (dark grey) up to 2" thick, trace of glauconite, some soft sediment boudinage, thinly bedded and slightly inclined, 360-370' minor intercalations with some cross-bedding, 370-380' sandstone now N7 (light grey) intercalated with shale beds up to 2" thick, 380-390' intercalated sandstone-shale 50:50, reworking in part with soft sediment boudinage; 312' lower medium, 320-330' very fine, 340' fine, 350-380' very fine
- 390- 572 $\frac{1}{2}$ ' Shale intercalated with sandstone, 390-400' shale with cross-bedded sandstone lenses up to 3" thick, 400-420' sandstone interbeds show soft sediment boudinage, 420-440' sandstone interbeds generally less than 2 $\frac{1}{2}$ " thick and are

thinly bedded, cross-bedded, or inclined, 440-500' shale N4 (medium dark grey) with cross-bedded sandstone lents, reworked in part, fair proportion of carbonaceous material, 500-572' sandstones now less than $\frac{1}{2}$ " thick and extremely minor, 572-572 $\frac{1}{2}$ ' get an argillaceous conglomerate with chert pebbles up to $\frac{3}{4}$ " in size, pyritic in part

572 $\frac{1}{2}$ -680' Sandstone, 10YR 6/2 (pale yellowish-brown), 570-580' very clean, porosity up to 8%, occasional stringers of argillaceous material, bedding slightly inclined, 580-590' slight color change to 5Y 6/1 (light olive-grey), porosity up to 5%, trace glauconite, fair proportion calcite flakes, 590-600' 10YR 6/2 (pale yellowish-brown) with occasional thin argillaceous beds up to 1/16" thick, 600-620' sandstone with major shale interbeds, sand 60%, shale 40%, soft sediment boudinage with minor reworking, 620-630' 5Y 7/2 (yellowish-grey), thinly bedded and slightly inclined, very well sorted, porosity up to 15%, 630-640' very thin argillaceous beds up to 1/32" thick, 640-660' same as 600-620' with sand 70%, shale 30%, 660-673' porosity 12%, presence of glauconite, fair sorting, very thin slightly inclined beds, 673-680' sandstone intercalated with shale, soft sediment boudinage, sand 70%, shale 30%; 572 $\frac{1}{2}$ -600' lower fine, 620-680' lower fine

680-941' Shale with sandstone interbeds, 680-700' shale 70%, sand 30%, 700-710' shale 90%, sand 10%, 710-879' shale, N4 (medium dark grey) with about 5% sand interbeds, silty shale ranges from 690-760' and soft shale from 760-879', 879-882' an argillaceous conglomerate with chert and sandstone clasts, 882-930' shale becoming harder, minor sand lenses, glauconitic in part, 930-941' shale 70%, sand 30%, soft sediment boudinage, minor reworking

941-990' Sandstone, N7-N8 (light grey to very light grey), 941-960' porosity up to 12%, fine grained, good sorting, with very thin shale laminations, 970-980' shale laminations becoming more abundant, 980-990' shale rapidly increasing, sand 60%, shale 40%, 989 $\frac{1}{2}$ -990' an argillaceous conglomerate 6" thick; 941-970' lower fine, 980-990' upper fine

990-1020' Shale, N4 (medium dark grey), 990-1000' intercalated shale-sandstone, shale 80%, sand 20%, 1000-1013' minor sandstone lents, soft sediment boudinage, lenses up to 3/4" thick, 1013-1020' predominantly paper shale, intercalations extremely minor

- C2 total depth 580' ground elevation 905'
- 10-30' Siltstone, 5Y 5/2 (light olive-grey), very fine grained, thin calcite bands, at 20' color change to 10Y 4/2 (greyish-olive), at 11' thin walled pelecypod shells and chert-like inclusions (?), at 12' porosity about 6%, abundant pelecypod shells over a 4' interval, 19' get shale laminations, 22' siltstone-shale with very fine grained lenses of sand trapped within the shale, trace of fossil wood, 25-30' re-appearance of scattered zones of pelecypod shells, 30' color change to 10Y 6/2 (pale olive)
- 30-70' Sandstone, 10Y 6/2 (pale olive), 30-35' localized concentrations of pelecypod shells ranging in size from a few mm to 1", 35-40' pockets of shell debris, sand quite friable, porosity 15%, 40-55' only occasional fossil debris, essentially uniform in color and composition, 55-60' color now 5Y 6/1 (light olive-grey) interbedded with dark grey silty shale with minor reworking and soft sediment boudinage, abundant cross-bedding with trace of microstylolites, 60-67' cross-bedding only feature observed and becomes less pronounced toward bottom; 40-70' lower fine
- 70-240' Shale intercalated with sandstone, 70-80' very fine grained sandstone 5GY 6/1 (greenish-grey) interbedded with shale, N3 (dark grey), sand occurs as lenses, soft sediment boudinage with cross-bedding up to 2" thick, 80-90' same as 70-80' except for occasional scattered pelecypod shells, 90-140' intercalated sandstone-shale, cross-bedded with up to 6" thick sand lenses, 140-150' sand lenses now less than 2" thick, 200-220' size of sand lenses decreasing considerably with the dark grey shale predominanting, sand lenses less than $\frac{1}{2}$ " thick, 220-240' lenses now become a type of lamination, 70-130' is sand 80%, shale 30%, 140-150' is sand 60% shale 40%, 150-200' is sand 50%, shale 50%, 200-240' is shale 80%, sand 20%.
- 240-268' Siltstone-sandstone, 10Y 6/2 (pale olive) with shale laminations and occasional rock fragments, glauconitic in part
- 268-311' Sandstone, N7 (light grey), 268-270 porosity 10-20%, glauconitic, moderate sorting, abundant shale lenses, 270-275' very fine grained with trace of glauconite, good porosity, relatively clean, 275-276 $\frac{1}{2}$ ' an argillaceous conglomerate with pebble range up to 1" in size, little or no glauconite, 276 $\frac{1}{2}$ -280' sand clean again, porosity up to 18%, 280-300' occasional thin laminations of argillaceous

material, very thinly cross-bedded in part, 305-311' gradational contact with interbedded sandstone and shale; 263' lower fine, 280-311' upper very fine to lower fine.

311-429'

Shale, N4 (medium dark grey), friable, intercalated with minor sand lenses, some soft sediment boudinage, 340-350' sand lenses increase in thickness and show cross-bedding in part, 350-380' trace of glauconite in some of the sand lenses, 380-390' occasional pelecypod shells, 429' gradational contact back into a sandstone.

429-550'

Sandstone, N6 to 5Y 6/1 (medium light grey to light olive grey), moderate sorting, abundant minor shale intercalations through-out and up to 15% in places, 430-450' scattered argillaceous laminations, 450-451' a conglomerate, very shaly, with chert pebbles, 451-460' fine grained sandstone, fairly argillaceous, fair sorting, trace of glauconite, porosity 15-20%, 460-470' 5Y 6/1 to 5GY 6/1 (light olive grey to greenish grey), very clean, good sorting, trace of glauconite, porosity 15-20%, 470-473' sandstone with abundant argillaceous laminations, 473-474' very clean sandstone, 474-480' as at 470-473', 510-535' clean sand, good sorting, porosity up to 20%, minor argillaceous laminations, 535-536' a chert pebble conglomerate with clasts up to 3/4" in size, 536-548' argillaceous laminations increase rapidly in quantity; 430' lower medium, 435-460' upper fine to very lower medium, 460-480' upper fine to lower medium, 480-500' upper fine, 500-510' lower medium, 510-550' upper fine.

550-580'

Shale, N5 (medium grey), friable, fairly uniform in composition, 560-570' shale with occasional 6-12" intervals of sandstone N7 (light grey), 570-580' friable shale with abundant pyrite, trace of carbonate cement.

APPENDIX B

Quantitative data for the authigenic minerals

Glc = glauconite
 Om = organic matter
 Sid = siderite
 Pyr = pyrite
 O/g = quartz overgrowths

Cham = chamosite
 Calc = calcite
 Fe = iron oxides
 Chl = chlorite

	Glc	Cham	Om	Calc	Sid	Fe	Pyr	Chl	O/g
F52A-1-503 ^o	7	-	4	2	-	-	3	2	2
F52A-4-540 ^o	-	-	2	6	-	-	1	3	3
F52A-5-555 ^o	-	-	2	14	-	-	1	5	3
F52A-7-565 ^o	2	-	4	1	-	-	2	-	2
F52A-8-570 ^o	2	7	5	-	45	4	1	-	2
F52A-10-580 ^o	tr	5	1	-	30	6	1	12	tr
F52A-14-600 ^o	2	2	2	-	24	2	-	15	tr
F52A-17-620 ^o	2	-	tr	tr	-	-	-	11	2
F52A-19-628 ^o	1	-	1	tr	-	-	-	9	3
F52A-20-635 ^o	5	-	3	1	-	tr	2	-	tr
F52A-22-658 ^o	4	-	8	-	-	-	5	-	tr
F52A-23-668 ^o	tr	-	tr	-	47	tr	3	-	-
F52A-25-697 ^o	5	-	2	17	-	-	2	-	1
F52A -721 ^o	1	-	6	2	-	2	2	-	tr
F52A -742 ^o	tr	-	2	25	-	1	3	-	-
F52A -761 ^o	1	-	5	2	-	2	2	-	3
F52A -795 ^o	tr	-	3	25	-	1	3	-	-
F52A -814 ^o	1	-	3	2	-	3	3	-	2
F52A-26-841 ^o	3	-	10	-	-	-	5	2	1
F52A-27-850 ^o	-	-	1	1	-	-	1	2	1
F52A-30-869 ^o	-	-	tr	2	-	-	1	3	6
F52A-31-880 ^o	-	-	tr	1	-	-	tr	1	2
F52A-33-890 ^o	1	-	3	1	-	-	tr	3	4
F52A-35-900 ^o	1	-	3	tr	-	-	2	-	1
F52A-37-910 ^o	3	-	tr	-	-	-	1	3	4
F52A-38-920 ^o	2	-	1	2	-	-	2	-	1
F52A-39-925 ^o	2	-	tr	-	40	-	3	-	tr
F52A-40-930 ^o	2	-	5	1	-	-	2	13	1
F52A-43-944 ^o	1	-	4	17	-	-	2	-	3
F52A-44-950 ^o	1	-	2	tr	-	-	2	-	2
F42-1-234 ^o	2	-	5	3	-	-	2	-	1
F42-3-258 ^o	6	-	3	1	-	-	1	-	2
F42-6a-285 ^o	6	-	4	-	10	-	2	-	2
F42-6b-285 ^o	12	-	7	-	30	-	1	-	-
F42-9-312 ^o	2	7	7	-	35	11	tr	-	tr
F42-11-327 ^o	2	7	1	-	31	2	1	-	tr
F42-16-335 ^o	2	6	2	1	-	-	2	4	5
F42-13-350 ^o	2	-	2	-	-	2	1	3	4

	Glc	Cham	Om	Calc	Sid	Fe	Pyr	Chl	O/g
F42-18-365 ^o	tr	-	3	-	-	-	2	1	3
F42-20-377 ^o	1	-	4	1	-	-	3	1	2
F42-22-396 ^o	3	-	4	tr	-	-	2	-	3
F42-426 ^o	1	-	3	2	-	1	1	-	1
F42-449 ^o	1	-	2	1	-	2	2	1	2
F42-27-471 ^o	1	-	4	3	-	-	2	-	1
F42-495 ^o	1	-	4	-	-	2	3	-	tr
F42-520 ^o	1	-	4	10	-	1	tr	-	-
F42-549 ^o	3	-	6	4	-	-	1	2	tr
F42-28-572 ^o	3	-	22	-	-	-	2	-	1
F42-30-585 ^o	2	-	2	1	-	tr	2	-	3
F42-32-595 ^o	2	-	tr	7	-	4	2	-	6
F42-34-610 ^o	2	-	2	1	-	4	1	-	3
F42-36-625 ^o	tr	-	5	2	-	-	2	-	2
F42-38-635 ^o	tr	-	2	2	-	5	3	-	2
F42-40-644 ^o	-	-	2	17	-	-	3	-	1
F42-41-648 ^o	-	-	1	tr	-	-	4	-	4
F42-44-665 ^o	2	-	1	4	-	-	1	-	3
F42-46-679 ^o	3	-	tr	1	-	-	4	-	3
F42-47-683 ^o	1	-	4	1	-	tr	1	-	4
F42-710 ^o	1	-	5	2	-	-	tr	2	1
F42-736 ^o	-	-	2	1	70	2	1	-	tr
F42-763 ^o	-	-	20	-	-	-	5	-	2
F42-795 ^o	-	-	4	2	5	-	1	-	tr
F42-843 ^o	1	-	15	-	-	-	1	-	1
F42-861 ^o	tr	-	tr	1	-	80	1	-	-
F42-48-880 ^o	6	-	7	-	8	-	1	-	2
F42-913 ^o	3	-	2	2	-	-	1	-	2
F42-50-934 ^o	2	-	1	1	-	-	tr	-	2
F42-52-955 ^o	-	-	1	-	-	-	tr	-	4
F42-55-970 ^o	1	-	tr	-	-	-	1	-	3
F42-57-980 ^o	1	-	tr	12	-	-	tr	-	3
F42-58-985 ^o	1	-	2	20	-	tr	1	-	3
F42-59-987 ^o	1	-	5	-	-	-	3	-	2
F42-60-990 ^o	-	-	-	7	-	-	3	-	1
C2-1-15 ^o	-	-	5	1	-	-	2	-	-
C2-23 ^o	-	-	10	-	-	2	-	4	2
C2-6-50 ^o	2	-	2	1	-	2	4	11	3
C2-9-68 ^o	2	-	tr	tr	9	2	2	6	2
C2-11-102 ^o	10	-	tr	tr	-	-	2	6	3
C2-120 ^o	tr	-	1	tr	tr	-	3	1	3
C2-132 ^o	1	-	tr	1	tr	tr	1	-	3
C2-14-161 ^o	2	-	tr	-	12	-	2	-	tr
C2-15-187 ^o	3	-	tr	-	25	-	4	-	-
C2-206 ^o	1	-	3	2	-	tr	2	-	2
C2-238 ^o	3	-	1	-	-	tr	1	2	3
C2-16-267 ^o	3	-	4	-	-	-	tr	-	2

	Glc	Cham	Om	Calc	Sid	Fe	Pyr	Chl	O/g
C2-18-275°	tr	-	-	tr	-	-	tr	-	5
C2-19-276°	-	-	2	-	-	-	-	-	-
C2-21-285°	1	-	tr	3	-	-	2	-	1
C2-22-290°	1	-	-	1	-	-	2	-	2
C2-25-305°	2	-	1	1	tr	-	1	-	2
C2-26-310°	1	-	tr	1	-	-	1	3	4
C2 -328°	1	-	3	-	-	2	6	-	1
C2 -350°	1	-	5	-	-	2	3	tr	3
C2 -372°	-	-	1	-	90	-	tr	-	-
C2 -408°	tr	-	70	-	-	-	1	-	-
C2-27-430°	1	-	8	tr	-	-	1	-	2
C2-28-435°	1	-	4	tr	-	-	1	-	3
C2-31-452°	2	-	3	tr	-	-	1	1	3
C2-33-462°	5	-	3	2	-	-	2	-	2
C2-35-475°	2	-	2	2	-	-	1	-	4
C2-38-501°	1	-	tr	tr	-	-	1	-	5
C2-42-533°	1	-	tr	-	-	-	2	-	5
C2-44-568°	tr	-	5	6	-	3	1	-	1

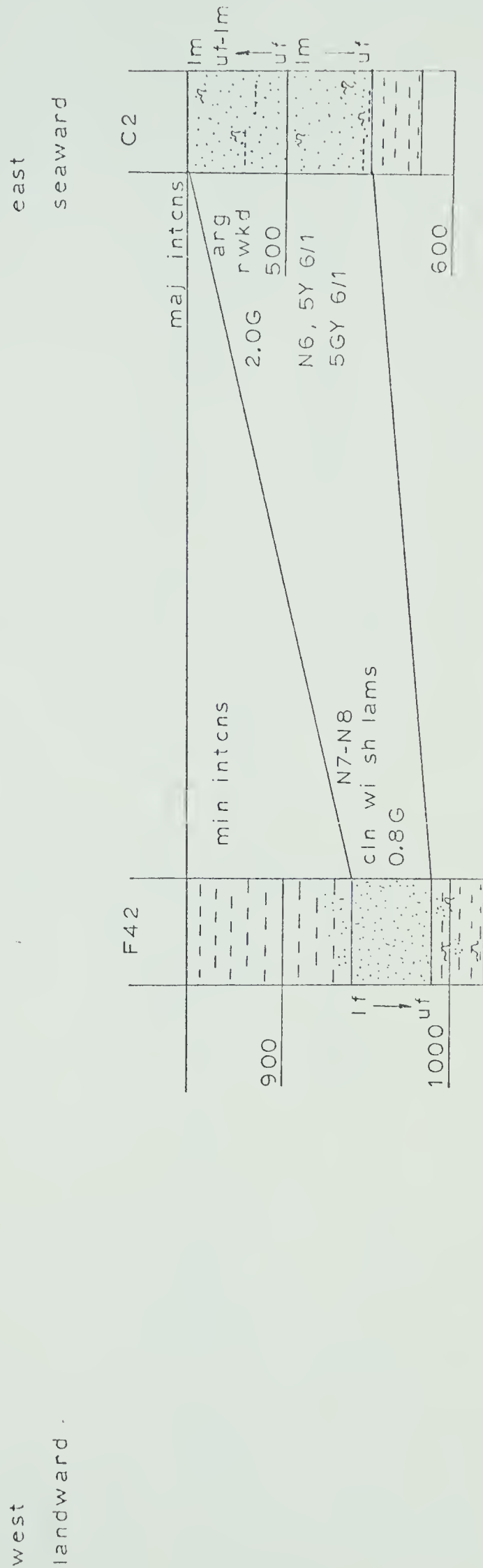
APPENDIX C

Stages in paleoenvironmental reconstruction

Legend:

min	=	minor
intens	=	intercalations
cln	=	clean
wi	=	with
sh	=	shale
lams	=	laminations
0.8G	=	.8 per cent glauconite etc.
arg	=	argillaceous
maj	=	major
lm	=	lower medium (grain size)
uf	=	upper fine (grain size)
rwkg	=	reworking (physical and organic)
v	=	very
sl	=	slightly
lf	=	lower fine (grain size)
uvf	=	upper very fine (grain size)
occ	=	occasional
glc	=	glauconitic
ss	=	sandstone
intbds	=	interbeds
fs	=	fossiliferous
inc	=	increase

landward part of shoal - undisturbed shale laminations, sparse glauc. with overlying shale showing minor intercalations / thicker sand must be adjacent to shoal because intercalation intensity increases in this direction / reworking reflected by color change seaward N7-N8 to 5Y 6/1-5GY 6/1

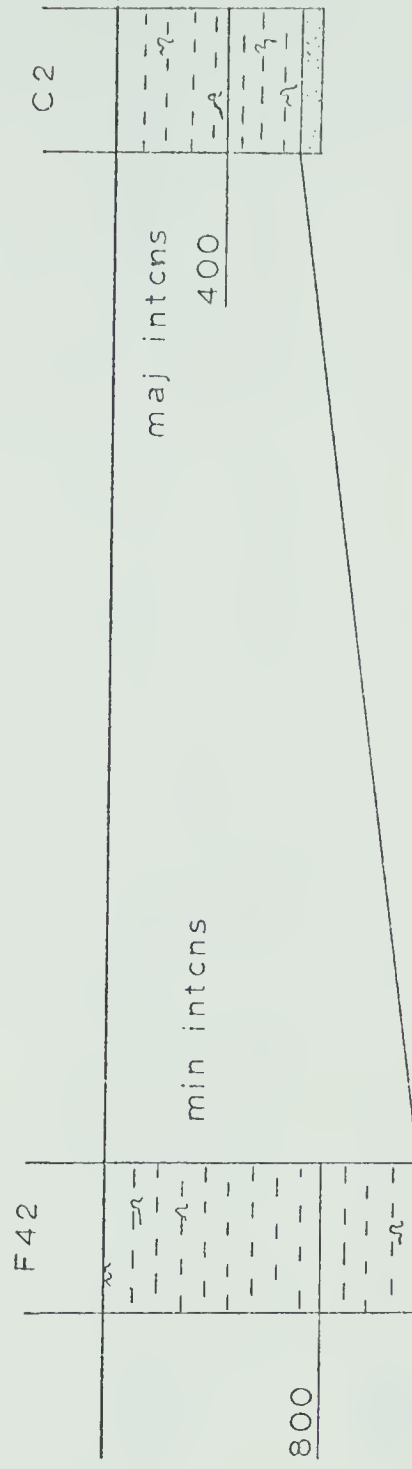


STAGE 1 (ZONE A)

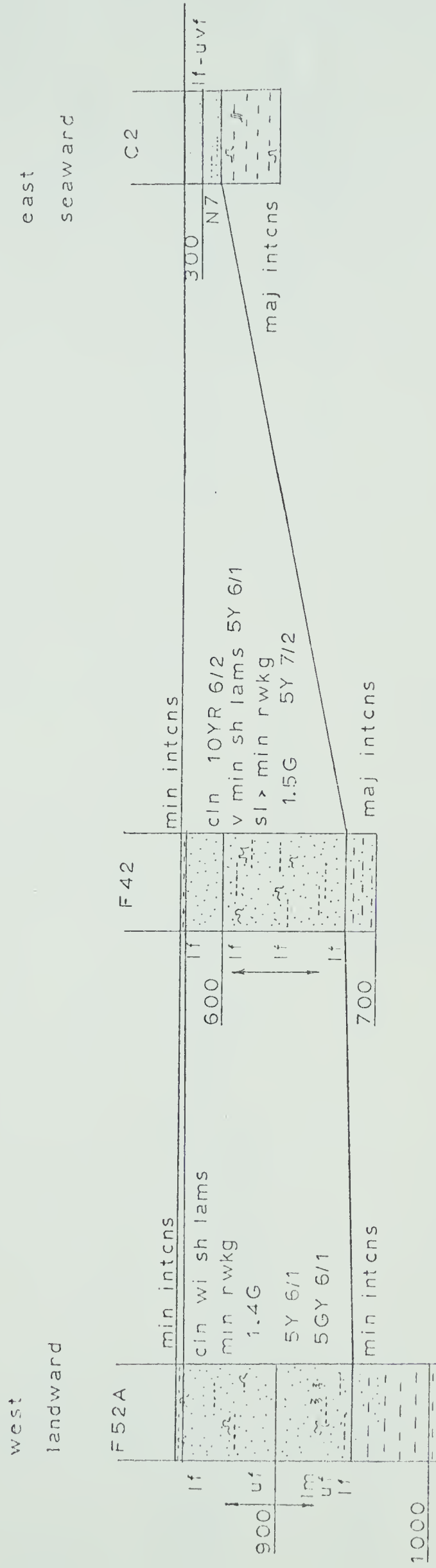
slight increase in subsidence in relation to sedimentation, i.e. a
transgression phase / major intercalations in seaward
direction

west
landward

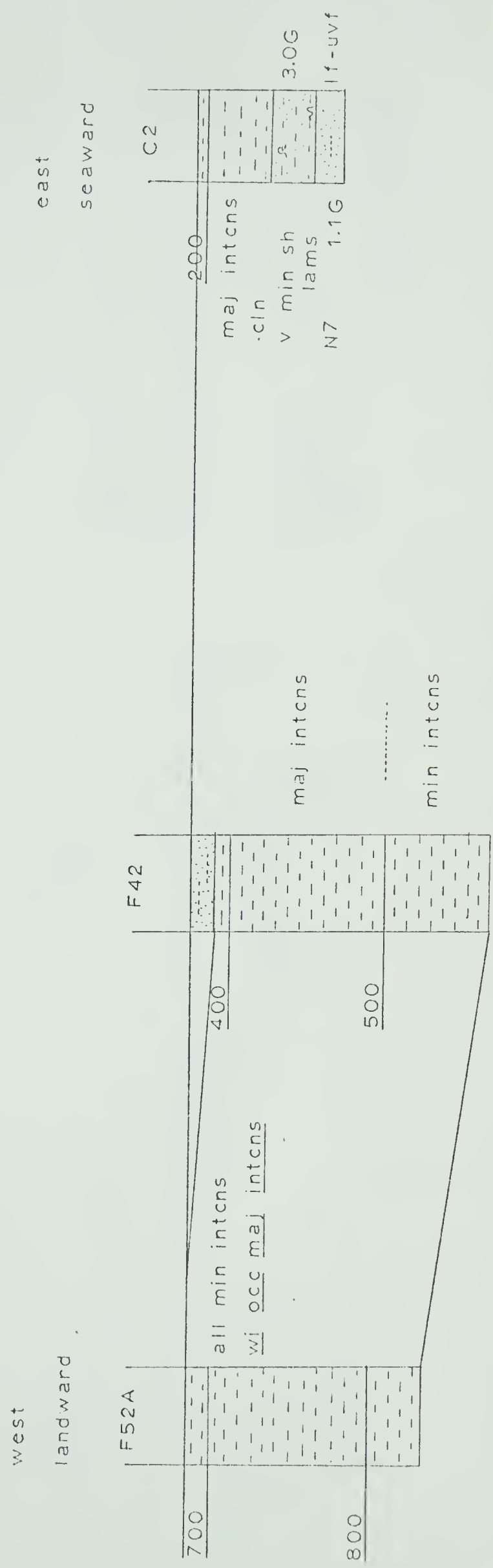
east
seaward



strandline shifts landward, regression, and stabilizes between subsidence and sedimentation / sand in C2 similar to sand of Zone A, F42 i.e. both seaward & landward sands appear the same in characteristics - clean with shale laminations, color, etc. / difference is in increase in glauconite in seaward direction / also seaward direction shows definite increase in degree of intercalations for the overlying shale

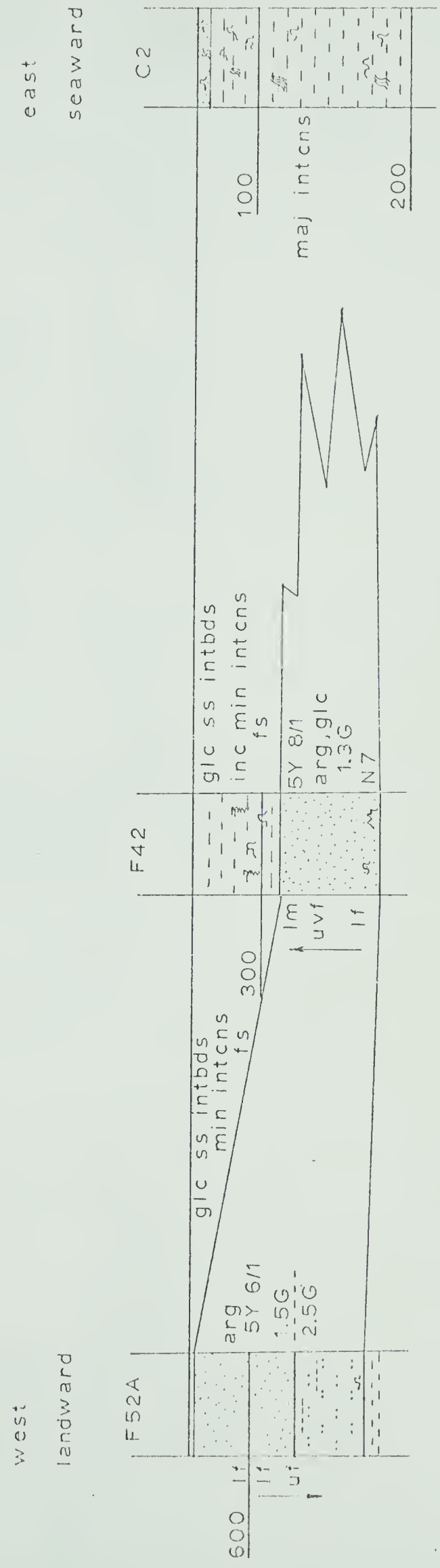


major subsidence in relation to sedimentation / no standstill sands
 developed / once again major intercalations as approach sea

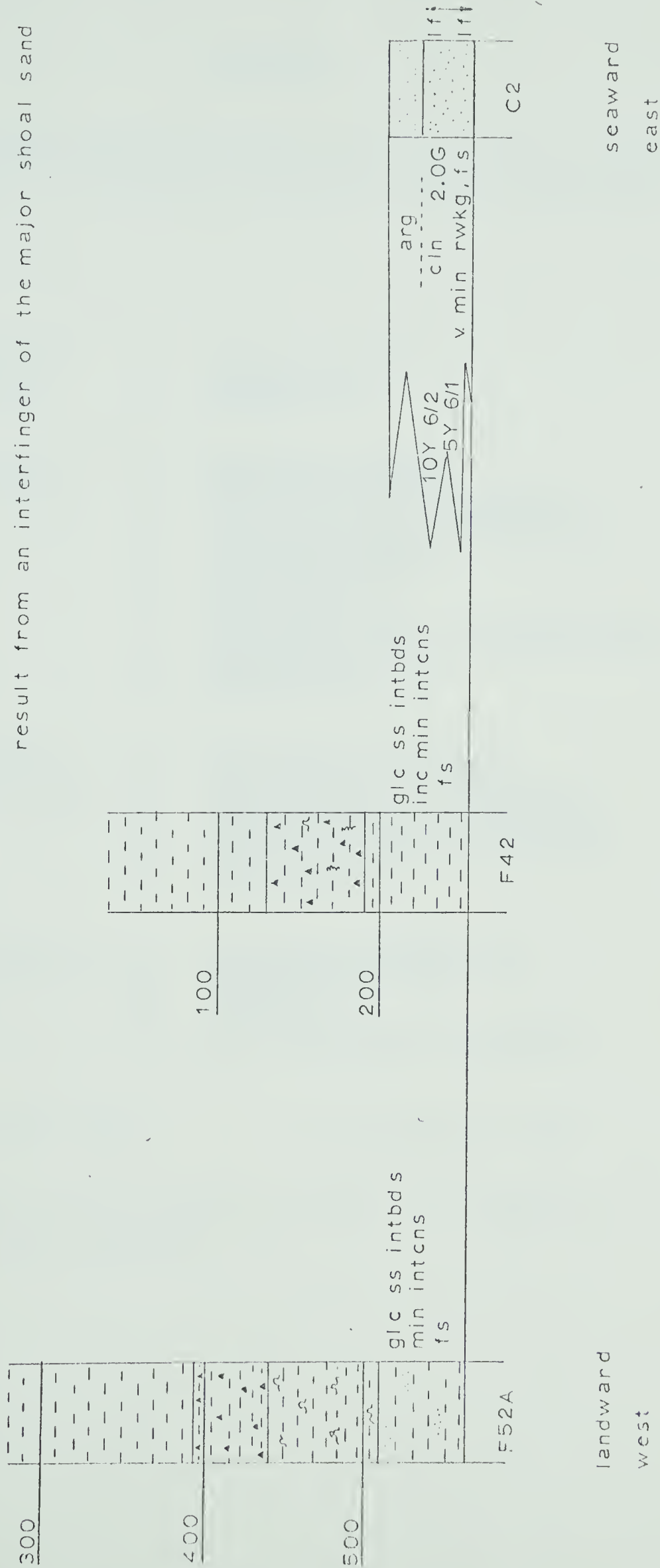


STAGE 4 (ZONE D)

shift in strandline seaward - regression which then becomes
 stabilized / shoal interfingers seaward into major intercalations /
 thick interbeds of glauconitic sandstone in shale with minor
 intercalations interfinger seaward with the sands and then give
 way to major intercalations in the C2 well / no doubt this is
 due to major subsidence associated with the base of Zone D
 (stratigraphic datum conglomerate)



strandline shifts seaward-transgression /
 glauconite content makes it similar to the seaward
 portion of the shoal but the fossil control would
 place it on the landward side / the glauconite may
 result from an interfinger of the major shoal sand



STAGE 6 (ZONE F)

APPENDIX D

Reconnaissance micropaleontological report on 4 lots of core samples from Imperial Oil Exploration Stony Creek F42 and F52A Wells.

Stony Creek F52A depth 523 feet	A	<u>Bathysiphon</u> sp.
	A	<u>Reophax</u> sp.
Stony Creek F42 depth 725-730 feet	A	<u>Gaudryina</u> <u>tappanae</u>
	A	<u>Haplophragmoides</u> <u>duoflatis</u>
	A	<u>Ammodiscus</u> cf <u>A. mackenziensis</u>
	A	? <u>Psammionopelta</u> sp.
	C	<u>Lenticulina</u> sp.
	C	<u>Saracenaria</u> sp.
	A	<u>Haplophragmoides</u> <u>H. goodenoughensis</u>
	A	<u>Saccamina</u> sp.
Stony Creek F42 depth 900-910 feet	A	<u>Ammobaculites</u> sp.
	A	<u>Bathysiphon</u> <u>scintillata</u>
	A	<u>Ammobaculites</u> <u>A. reophacoides</u>
	A	? <u>Thuramminoides</u> <u>T. septagonalis</u>
	A	<u>Haplophragmoides</u> <u>H. neocomiana</u>
	A	<u>Trochammina</u> sp.
Stony Creek F42 depth 1010-1020 feet	A	<u>Ammodiscus</u> <u>mackenziensis</u>
	A	? <u>Glomospirella</u> sp.
	A	<u>Reophax</u> sp.
	A	<u>Haplophragmoides</u> <u>H. duoflatis</u>

A = agglutinated foram

C = calcareous foram

*Data supplied by T. P. Chamney of the G. S. C. (Calgary)
Report No. Mes. 3 TPC 1970

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